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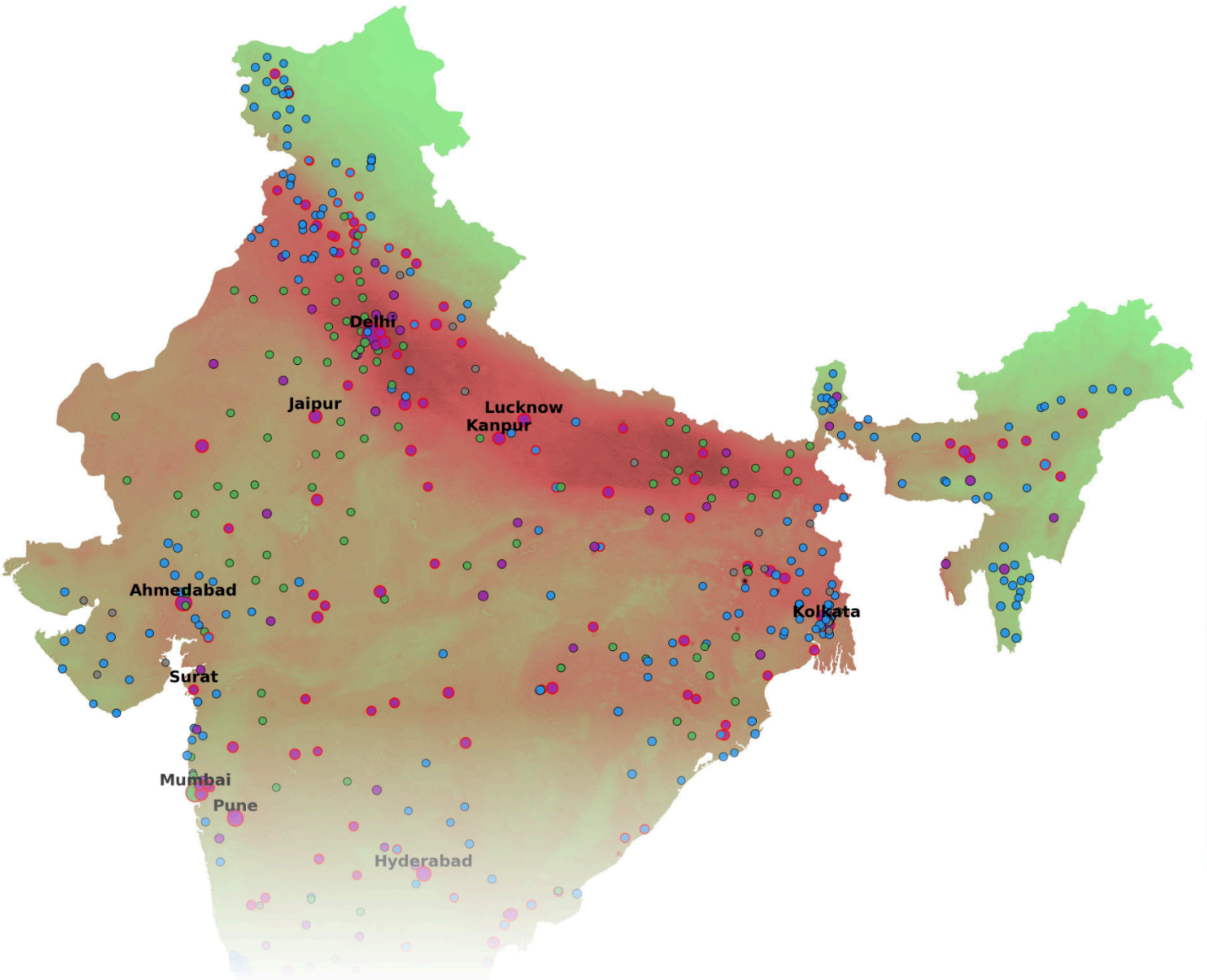
Air Quality Data Accessibility in India:

Distribution, Gaps, and Network Correlations

A spatial analysis of air quality monitoring stations across states, districts, and cities



Introduction

The aim of this study is to examine and verify the availability of air quality data across India. Although numerous tools exist for estimating air pollution, we limit our analysis to observation systems that provide confirmed and systematically collected measurements. Monitoring networks based solely on approximate modeling or on sensors that do not undergo regular calibration procedures are excluded from this study. We focus on the national systems for which **Central Pollution Control Board (CPCB) [1]** publishes structured station inventories and standardized data: the manual **National Air Monitoring Programme (NAMP)** network and the Real-Time system, which includes **Continuous Ambient Air Quality Monitoring network (CAAQM)** as well as other automatic networks operated by different organizations, including **System of Air Quality and Forecasting And Research (SAFAR) [2]**, but reporting their measurements to CPCB through a unified protocol. Taken together, these sources allow us to assess how publicly accessible air quality information is distributed across Indian states, districts, and cities.

The report compares the presence and density of monitoring stations across states, districts, and major cities, highlighting imbalances and identifying regions with limited coverage. It also explores correlations between the number of stations and parameters such as population, area, population density, and average air pollution levels.

Relevance of the Study

By 2026, India has made substantial progress in deploying large-scale air quality monitoring systems, particularly through the expansion of the CAAQM network and the operational development of SAFAR in several metropolitan regions. However, significant gaps persist in spatial coverage and, critically, in public access to timely air quality information across many states and districts. Real-time data are available only from automated networks, whereas manual NAMP observations require laboratory processing and are published with considerable delay.

The importance of continuous, high-resolution monitoring extends beyond technical considerations and has been demonstrated through large-scale empirical evidence. In 2013, China launched a nationwide program to monitor air quality and disclose real-time pollution data to the public. As documented by Barwick et al. (2023) [3], the initiative substantially increased public access to pollution information and triggered measurable behavioral responses, including reduced outdoor exposure and higher demand for protective measures. These adjustments mitigated the mortality impact of air pollution, and conservative estimates suggest that the associated health benefits exceeded program costs by an order of magnitude. The findings underscore the broader value of transparent, real-time environmental information systems, particularly in developing countries facing severe air pollution but lacking robust data collection and dissemination infrastructure.

This conclusion is consistent with international regulatory guidance. The WHO Global Air Quality Guidelines explicitly state that effective implementation of air quality standards requires the existence and operation of monitoring systems, public access to air quality data, legally binding and harmonized standards, and structured air quality management systems [4]. In addition, WHO technical guidance recommends that continuous outdoor air monitoring should be encouraged for regulatory purposes [5], reinforcing the necessity of sustained, systematic measurements rather than episodic or delayed reporting.

Despite the growing role of automated systems, manual monitoring remains indispensable. NAMP stations measure a broader spectrum of pollutants—including metals and complex aerosols—that are not available from many continuous sensors. Manual observations also provide baseline calibration for automatic monitors and are required for validating satellite-based air quality products. Therefore, an effective national monitoring framework must combine both automatic and manual stations, each serving distinct scientific and regulatory purposes.

In parallel with government networks, India hosts an extensive ecosystem of private, municipal, industrial, and community-operated sensor networks. These systems often provide fine-scale, hyperlocal information but vary widely in transparency and public accessibility. While these data significantly increase observational density, the lack of publicly accessible platforms significantly reduces the value of the data.

The SAFAR network, operated by the Indian Institute of Tropical Meteorology, adds an additional layer of automated monitoring combined with meteorological modeling and short-term forecasting. SAFAR currently operates in Delhi, Mumbai, Pune, and Ahmedabad, providing real-time pollutant concentrations and predictive air quality indices. Although SAFAR is not a nationwide system and its methods and aims differ from CAAQM, its presence enhances operational capabilities in major metropolitan areas and improves public access to near-real-time information.

A comprehensive assessment of how monitoring stations are distributed across India is necessary in order to identify geographic imbalances in coverage and to determine where additional stations are required and where existing capacity may already be sufficient. Such an evaluation enables evidence-based planning of further network expansion, prioritizing underserved regions while avoiding redundant deployment in adequately covered areas. Strengthening monitoring capacity in locations where gaps persist remains essential for improving public-health preparedness, supporting environmental governance, and ensuring that residents have access to timely and actionable air quality information.

Data

This study uses publicly available datasets that describe the composition and spatial distribution of India's national air quality monitoring networks, including CAAQM, NAMP, and SAFAR. These datasets provide information on the locations and characteristics of monitoring stations across multiple states and cities. To complement the station inventories and to enable nationwide comparisons, additional global datasets on air quality, population distribution, and settlement geography were used. The combination of these sources allows a consistent assessment of monitoring coverage at the state, district, and city levels.

The research utilizes data provided by the Air Quality Data Portal of CPCB [7], including hourly observations from 2009 to 2025. These data were used to determine the number of days when automatic monitoring stations were operational.

To assess the spatial coverage of the CAAQM network across Indian states, districts, and cities, we use the latest publicly available list of CAAQM stations (November 2025) obtained from the Air Quality Data Portal of CPCB [7]. The list includes station names, their administrative locations, and information on the organizations responsible for operating the stations.

We incorporate the latest available list of NAMP stations (November 2024) published by the Official Website CPCB [1]. The list holds the names of the settlements where NAMP stations are located, their state assignments, and the number of manual monitoring stations operating in each city, town or village.

To identify station's locations, settlement names were matched to national geospatial datasets of Indian cities and towns. Because many Indian settlements have multiple spellings or transliteration variants, a degree of positional uncertainty is possible despite manual verification.

A list of non-attainment cities published by the Official Website CPCB [1] under the National Clean Air Programme (NCAP) was also used. This list identifies cities that did not meet the National Ambient Air Quality Standards over several consecutive years and was used to analyze the monitoring coverage in areas with persistently elevated pollution levels.

Information on SAFAR stations was obtained from the IITM monitoring portal [2]. The website provides the locations of stations, their geographic coordinates, and the organizations responsible for operating them. The system currently covers Delhi, Mumbai, Pune, and Ahmedabad.

Also, we use the global high-resolution PM2.5 dataset produced by the Atmospheric Composition Analysis Group (Washington University) [8]. It combines: satellite aerosol optical depth retrievals (MODIS, MISR, VIIRS), GEOS-Chem chemical transport modeling, available ground-based calibration data. Resolution for India is approximately 1 km.

For population and settlement data, we used several publicly available sources.

GHSL provides gridded population estimates derived from remote sensing and downscaled census data at a 100-m spatial resolution, allowing analysis of population density at district and city levels [9].

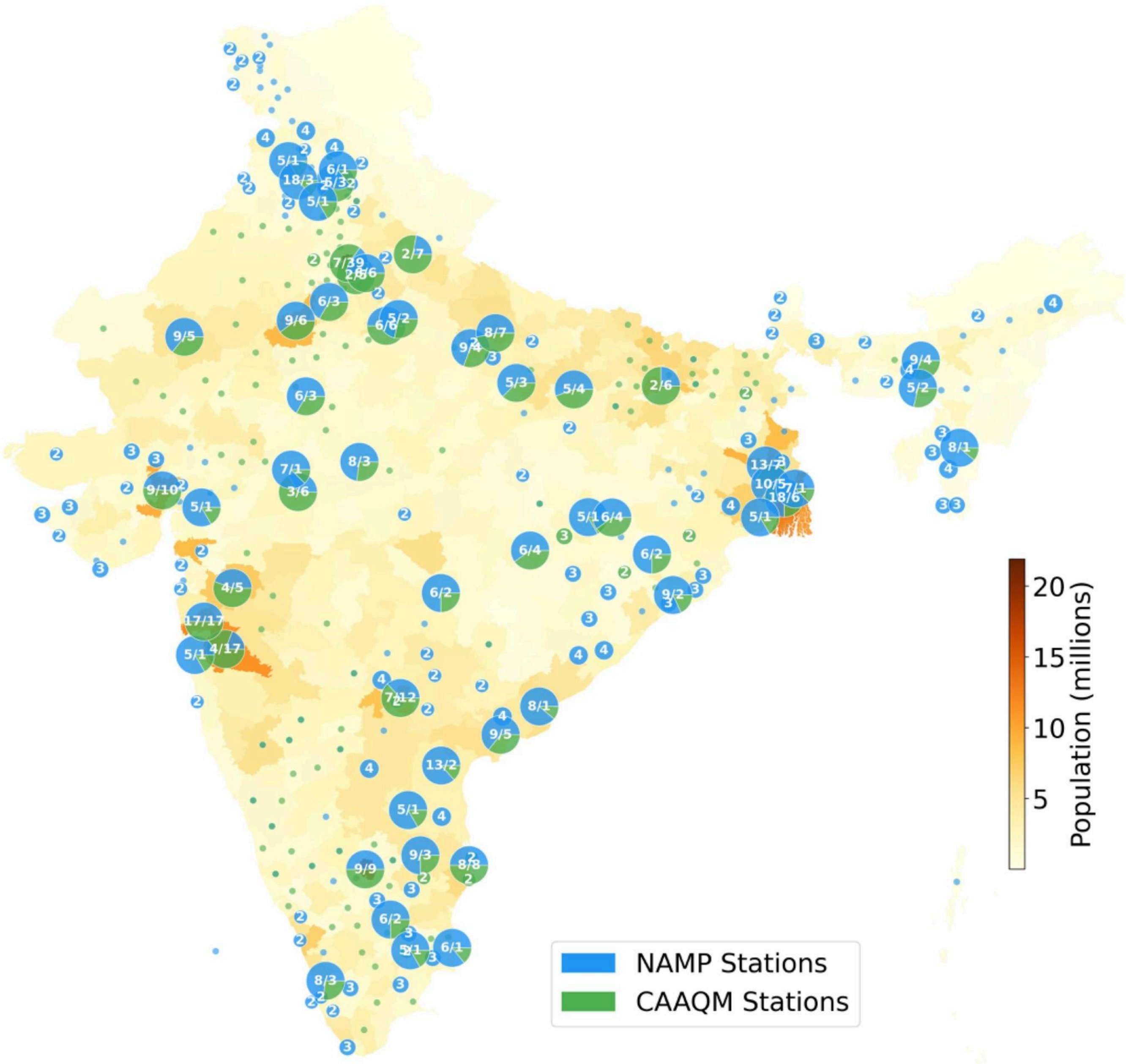
The UN World Urbanization Prospects — Urban Agglomerations dataset includes population estimates for all Indian urban agglomerations with ≥300,000 inhabitants [10]. These estimates, based on national censuses, demographic projections, and standardized UN methodologies, were prepared in 2019 for the 2025 projection year.

Since the full geospatial files from the 2011 Census were not readily obtainable for direct download, settlement-level information was accessed through the SHRUG dataset [11]. SHRUG provides geocoded settlements, census population counts, and administrative hierarchies, and was used to resolve station's locations and to classify cities and towns across India.

Additional Notes: variations in spelling of Indian place names occasionally required manual disambiguation.
All geospatial datasets were harmonized to EPSG:4326, and settlement and station names were standardized before analysis.

Overview of Indian government air quality monitoring networks

As of 2025 the national air quality monitoring framework in India includes **966 NAMP stations**, **562 CAAQM stations**, and **SAFAR network includes 42 sites.**



NAMP and CAAQM per district

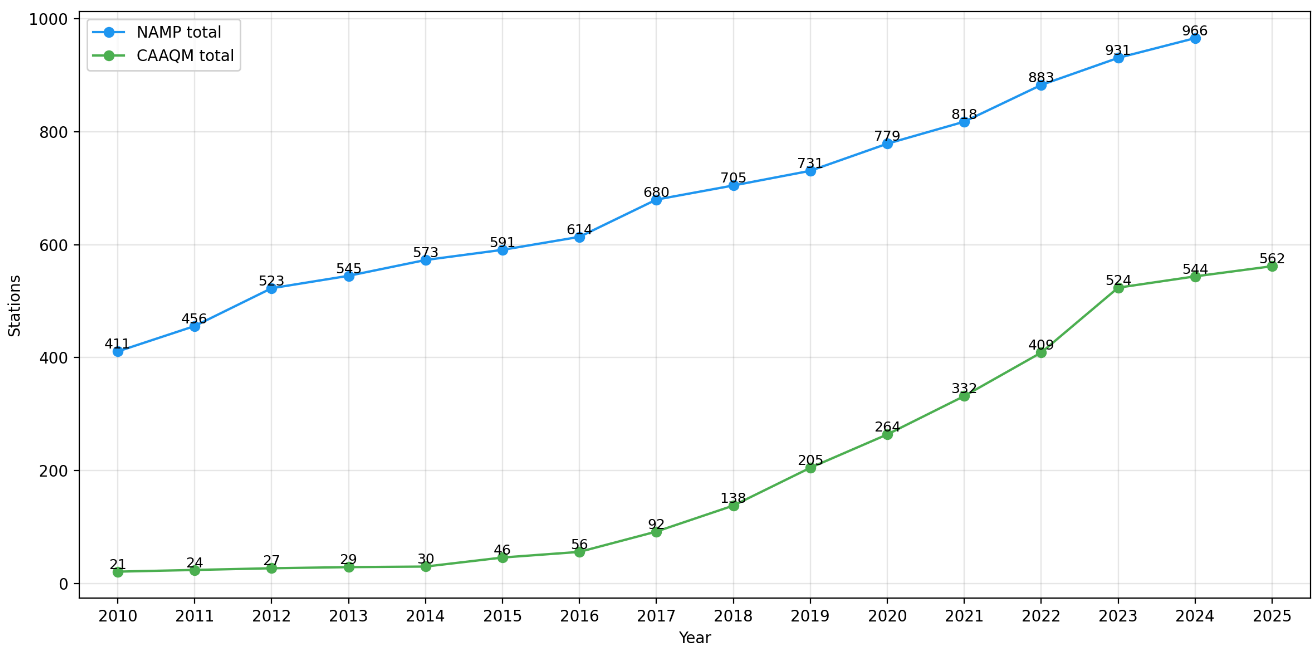
NAMP, established in the mid-1980s, represents India's longest-running manual sampling program.

CAAQM, introduced in the early 2000s, marked India's transition toward automated real-time air quality measurement, expanding gradually across major urban and industrial centers.

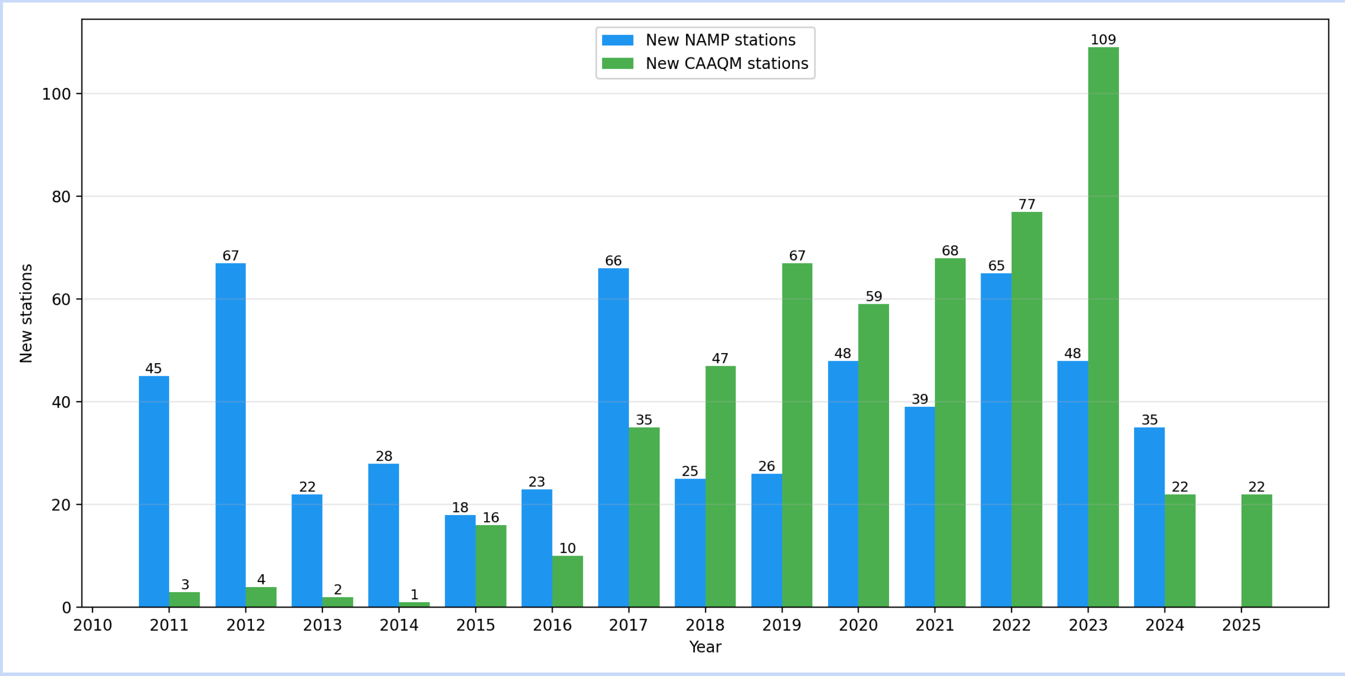
SAFAR, developed by IITM in the 2010s under the Ministry of Earth Sciences, was launched to provide city-level forecasts and real-time observations in selected metropolitan areas.

Development of Government Monitoring Networks and Siting Guidelines

According to information provided by the Government of India in responses to parliamentary questions on the status of air quality monitoring infrastructure, India's national system before 2010 was dominated by the manual NAMP network, which had expanded steadily across major cities and industrial regions since the 1980s. Automatic CAAQM stations existed only in small pilot numbers during this period, with fewer than thirty operational sites nationwide by the late 2000s.



Over the following decade, NAMP continued to expand, with new stations added each year according to data available through 2024. CAAQM showed a rising growth trend, with annual installations increasing up to a peak in 2023, after which the pace of expansion declined.



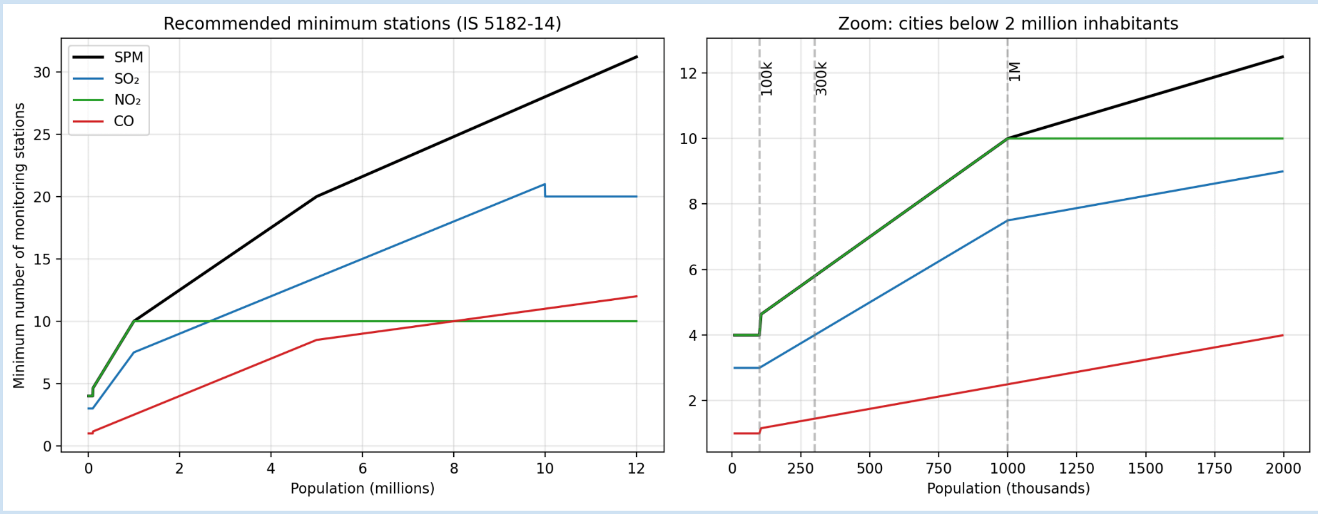
We did not identify any publicly available documents that specify siting requirements or minimum densities for automatic monitoring stations. However, the Guidelines for Ambient Air Quality Monitoring issued in 2003 by the Central Pollution Control Board (Ministry of Environment & Forests), together with Indian Standard IS 5182-14 (2000), *Methods for Measurement of Air Pollution, Part 14: Guidelines for Planning the Sampling of Atmosphere* [12], provide population-based recommendations for the minimum number of monitoring stations required in Indian cities. These documents form the principal regulatory basis for planning the spatial distribution of ambient air quality monitoring networks in India.

Table 2 Recommended Minimum Number of Stations, Population-Wise

(Clause 10.7.2.2*)*

Pollutant	Population of Evaluation Area	Minimum No. of AAQ Monitoring Station
(1)	(2)	(3)
SPM (Hi-Vol)	< 100 000	4
	100 000 - 1 000 000	4 + 0.6 per 100 000 population
	1 000 000 - 5 000 000	7.5 + 0.25 per 100 000 population
	>5 000 000	12 + 0.16 per 100 000 population
SO_2 (Bubbler)	<100 000	3
	100 000 - 1 000 000	2.5+0.5 per 100 000 population
	1 000 000 - 10 000 000	6 + 0.15 per 100 000 population
	> 10 000 000	20
NO_2 (Bubbler)	<100 000	4
	100 000 - 1 000 000	4 + 0.6 per 100 000 population
	>1 000 000	10
CO	<100 000	1
	100 000 - 5 000 000	1 + 0.15 per 100 000 population
	>5 000 000	6 + 0.05 per 100 000 population
Oxidants	- do -	- do -

According to the table included in the Guidelines, cities with populations below 100,000 should operate at least four stations, while cities of one to five million residents require between approximately 6 and 8 stations depending on pollutant type. For the largest metropolitan areas—those exceeding five or ten million people—the recommended minimum increases to 10–20 stations, again varying by pollutant category (SPM, SO_2, NO_2, CO). These values represent population-based norms for planning urban ambient air quality monitoring networks. Historically, they were primarily applied in the development of the NAMP station network, although the same planning principles can also be used when expanding automated monitoring systems such as CAAQM.



In practice, air quality monitoring stations deployed in India consistently measure particulate matter, including $PM_{2.5}$, while the broader set of pollutants monitored may vary between stations and networks. For this reason, the station-density recommendations associated with particulate matter (SPM) are used here as the reference benchmark.

Monitoring Methods and Parameters

CAAQM stations measure multiple pollutants continuously, typically including $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, O_3, NH_3, and Benzene, with hourly data transmission. In practice, some stations operate as integrated atmospheric monitoring platforms and additionally record NO, NO_x, volatile organic compounds such as Toluene and Xylene, as well as meteorological parameters including temperature, humidity, wind speed and direction, solar radiation, barometric pressure, and precipitation.

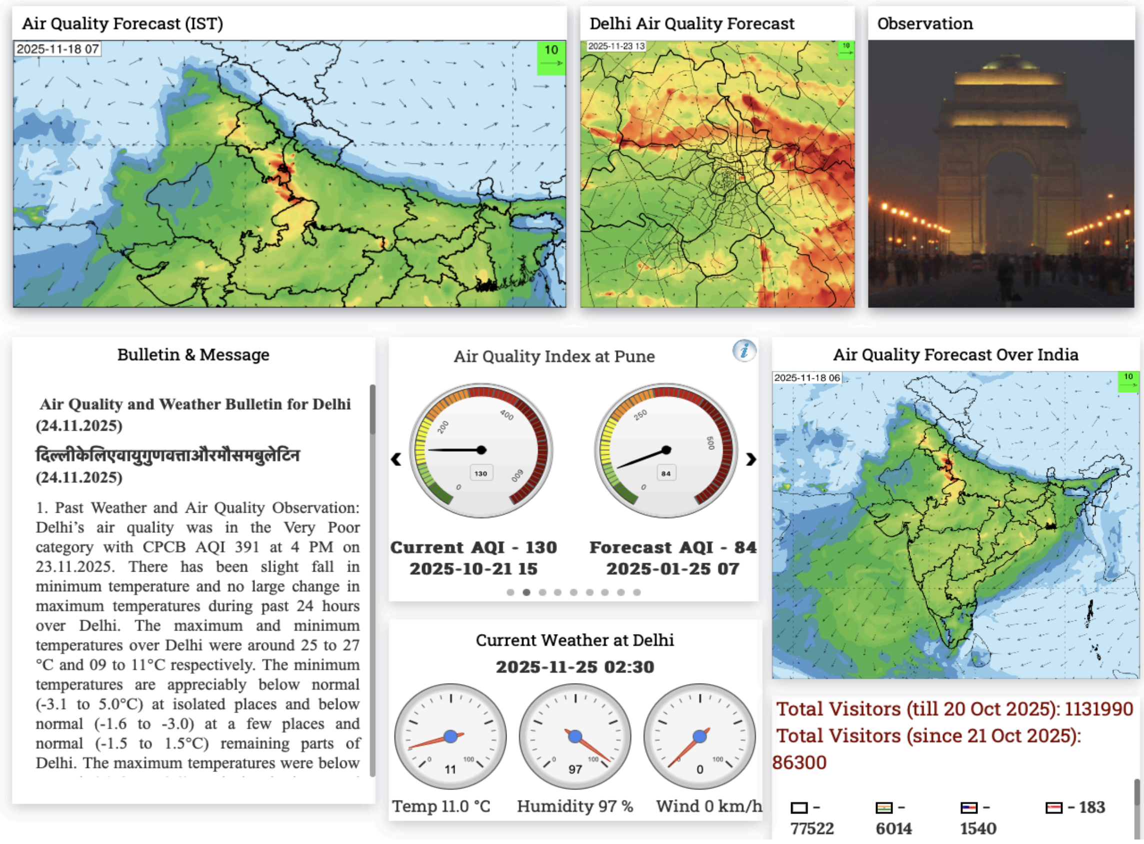
Parameters	From Date	To Date	Concentration	Unit	Standard	Concentration (previous 24 Hours)	Remarks
PM2.5	02 Dec 2025 16:30	02 Dec 2025 16:45	74	ug/m3	60 (ug/m3)	74.53	
PM10	02 Dec 2025 16:30	02 Dec 2025 16:45	183	ug/m3	100 (ug/m3)	125.19	
NO	02 Dec 2025 16:30	02 Dec 2025 16:45	3.3	ug/m3		9.28	
NO2	02 Dec 2025 16:30	02 Dec 2025 16:45	25.9	ug/m3	80 (ug/m3)	23.94	
NOx	02 Dec 2025 16:30	02 Dec 2025 16:45	16.6	ppb		20.27	
NH3	02 Dec 2025 16:30	02 Dec 2025 16:45	15.5	ug/m3	400 (ug/m3)	13.55	
SO2	02 Dec 2025 16:30	02 Dec 2025 16:45	2.6	ug/m3	80 (ug/m3)	2.89	
CO	02 Dec 2025 16:30	02 Dec 2025 16:45	1.61	mg/m3	4**(mg/m3)	0.99	
Ozone	02 Dec 2025 16:30	02 Dec 2025 16:45	22.7	ug/m3	180** (ug/m3)	24.09	
Benzene	02 Dec 2025 16:30	02 Dec 2025 16:45	0	ug/m3		0	
Toluene	02 Dec 2025 16:30	02 Dec 2025 16:45	0	ug/m3		0	
Xylene	02 Dec 2025 16:30	02 Dec 2025 16:45	0	ug/m3		0	
AT	02 Dec 2025 16:30	02 Dec 2025 16:45	34.4	degree C		31.91	
Temp	02 Dec 2025 16:30	02 Dec 2025 16:45	30.7	degree C		28.97	
RH	02 Dec 2025 16:30	02 Dec 2025 16:45	53	%		69.24	
WS	02 Dec 2025 16:30	02 Dec 2025 16:45	1.9	m/s		1.29	
WD	02 Dec 2025 16:30	02 Dec 2025 16:45	357	deg		351.76	
VWS	02 Dec 2025 16:30	02 Dec 2025 16:45	-36.5	m/s			Under Scrutiny
SR	02 Dec 2025 16:30	02 Dec 2025 16:45	764	W/mt2		763.83	
BP	02 Dec 2025 16:30	02 Dec 2025 16:45	711	mmHg		711.53	
RF	02 Dec 2025 16:30	02 Dec 2025 16:45	0	mm		0	

**Prescribed Standards for CO and CO is one hour Average

Online measurement results from the Zoo Park monitoring station in Hyderabad

NAMP measurements are conducted over a 24-hour period (4-hourly sampling for gaseous pollutants and 8-hourly sampling for particulate matter) with a frequency of twice per week, resulting in 104 observations per year. The program primarily monitors $PM_{2.5}$, PM_{10}, SO_2, and NO_2.

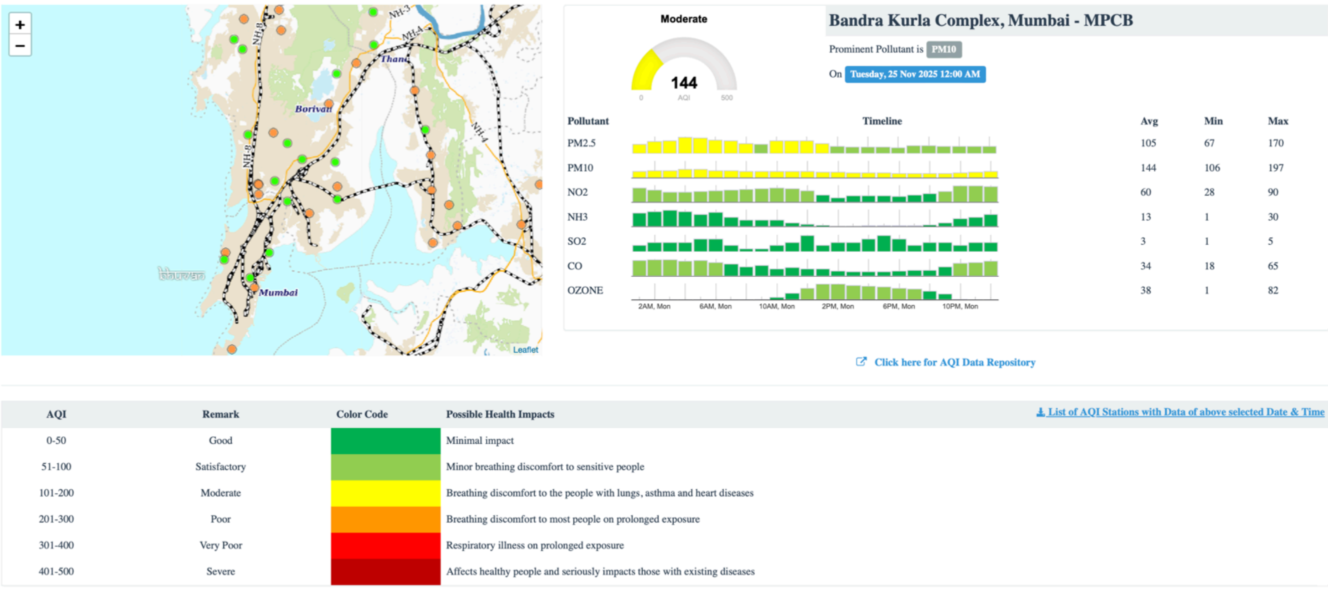
SAFAR in addition to pollutant concentration data integrates meteorological observations and predictive modeling to provide short-term air quality forecasts.



Weather and air quality forecasts by SAFAR

Public data access

Real-time air quality data from the CAAQM network are available to the public through Central Pollution Control Board's (CPCB) online dashboards and interactive map by regions and full network view.

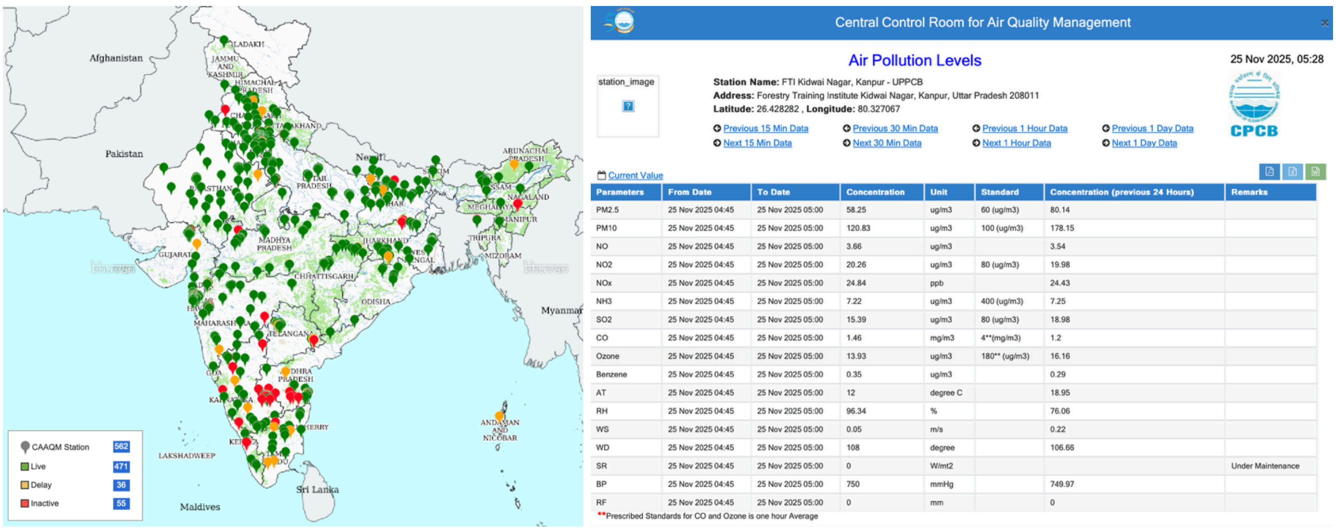


Pollutant	Avg	Min	Max
PM2.5	105	67	170
PM10	144	106	197
NO2	60	28	90
NH3	13	1	30
SO2	3	1	5
CO	34	18	65
OZONE	38	1	82

AQI	Remark	Color Code	Possible Health Impacts
0-50	Good		Minimal impact
51-100	Satisfactory		Minor breathing discomfort to sensitive people
101-200	Moderate		Breathing discomfort to the people with lungs, asthma and heart diseases
201-300	Poor		Breathing discomfort to most people on prolonged exposure
301-400	Very Poor		Respiratory illness on prolonged exposure
401-500	Severe		Affects healthy people and seriously impacts those with existing diseases

Region-level air quality monitoring by CAAQM

It is important to note that All-India map display the availability of monitoring stations, not the real-time pollution levels across the entire country. Users can view current readings for each active station by selecting its marker on the map.



Parameters	From Date	To Date	Concentration	Unit	Standard	Concentration (previous 24 Hours)	Remarks
PM2.5	25 Nov 2025 04:45	25 Nov 2025 05:00	58.25	ug/m3	60 (ug/m3)	80.14	
PM10	25 Nov 2025 04:45	25 Nov 2025 05:00	120.83	ug/m3	100 (ug/m3)	178.15	
NO	25 Nov 2025 04:45	25 Nov 2025 05:00	3.66	ug/m3		3.54	
NO2	25 Nov 2025 04:45	25 Nov 2025 05:00	20.26	ug/m3	80 (ug/m3)	19.98	
NOx	25 Nov 2025 04:45	25 Nov 2025 05:00	24.84	ppb		24.43	
NH3	25 Nov 2025 04:45	25 Nov 2025 05:00	7.22	ug/m3	400 (ug/m3)	7.25	
SO2	25 Nov 2025 04:45	25 Nov 2025 05:00	15.39	ug/m3	80 (ug/m3)	18.98	
CO	25 Nov 2025 04:45	25 Nov 2025 05:00	1.46	mg/m3	4**(mg/m3)	1.2	
Ozone	25 Nov 2025 04:45	25 Nov 2025 05:00	13.93	ug/m3	180** (ug/m3)	16.16	
Benzene	25 Nov 2025 04:45	25 Nov 2025 05:00	0.35	ug/m3		0.29	
AT	25 Nov 2025 04:45	25 Nov 2025 05:00	12	degree C		18.95	
RH	25 Nov 2025 04:45	25 Nov 2025 05:00	96.34	%		76.06	
WS	25 Nov 2025 04:45	25 Nov 2025 05:00	0.05	m/s		0.22	
WD	25 Nov 2025 04:45	25 Nov 2025 05:00	108	degree		106.66	
SR	25 Nov 2025 04:45	25 Nov 2025 05:00	0	W/mt2			Under Maintenance
BP	25 Nov 2025 04:45	25 Nov 2025 05:00	750	mmHg		749.97	
RF	25 Nov 2025 04:45	25 Nov 2025 05:00	0	mm		0	

**Prescribed Standards for CO and Ozone is one hour Average

All-India map by CAAQM and details per current station

CPCB also publishes daily air quality bulletins summarizing national and regional AQI results. In addition to the online dashboards, CPCB provides open access to downloadable CAAQM data for further analysis. A public repository offers historical measurements for most stations starting from

2017, and for some locations data are available from as early as 2009. This enables users and researchers to conduct independent analyses of long-term trends and data completeness.

Although the CAAQM dashboards provide real-time access to station-level observations, data from some stations may periodically become unavailable. In certain cases, these gaps can persist for extended periods, which limits users' ability to obtain timely information on local air quality. On online-board CPCB available station-level availability reports showing operational days and data completeness.

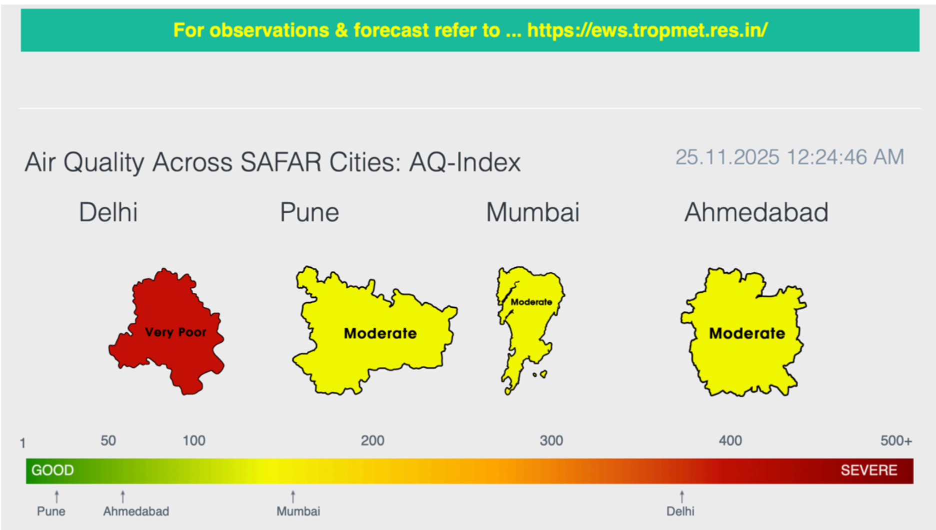
Bandra Kurla Complex, Mumbai - IITM Mumbai, Maharashtra

View Report

Year	January	February	March	April	May	June	July	August	September	October	November	December
2025	NA	NA	NA	24	27	30	28	30	28	27	16	NA
2024	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2023	31	27	31	27	28	30	12	20	30	30	29	27
2022	30	27	31	27	26	30	27	31	27	31	29	30
2021	31	28	31	30	30	25	29	25	30	31	30	30
2020	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	21	31

Availability report by CAAQM

The SAFAR system, developed by IITM under the Ministry of Earth Sciences, provides publicly accessible information on air quality in four metropolitan areas — Delhi, Mumbai, Pune, and Ahmedabad. The SAFAR portal offers real-time measurements together with health-oriented guidance and practical recommendations based on current air quality conditions, while the Early Warning System (EWS) platform provides model-based forecasts. Measurements from most SAFAR stations are also available through CPCB's air quality data services, where they are integrated with other real-time monitoring networks.



Air quality data on SAFAR portal

Data from the NAMP manual monitoring network are also publicly accessible, though with a time delay due to laboratory sampling and validation processes. At present, the latest published dataset corresponds to 2023, available through CPCB's manual monitoring portal.

Overall, while SAFAR provides user-friendly real-time information and guidance for a limited number of metropolitan areas, and NAMP offers the widest station count and broad geographic reach through manual monitoring, the combination of nationwide coverage and operational data availability is most consistently met by the CAAQM network. For this reason, the subsequent sections of this report examine the spatial distribution and data accessibility of CAAQM stations in greater detail.

Network density and air pollution levels

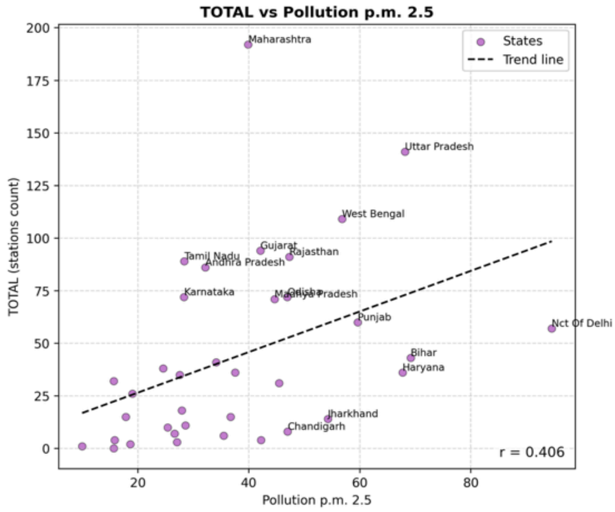
We focus our comparison on $PM_{2.5}$ concentrations, following the same rationale as in previous Airvoice studies: $PM_{2.5}$ is the pollutant most consistently associated with adverse health outcomes, and its concentration has a strong documented correlation with per-capita respiratory diseases. This makes $PM_{2.5}$ the most informative and widely used indicator for evaluating the adequacy of air quality monitoring coverage across India.

To support this comparison, we use annual mean $PM_{2.5}$ concentrations for the period 2019–2024 derived from a high-resolution global dataset produced by the Atmospheric Composition Analysis Group.

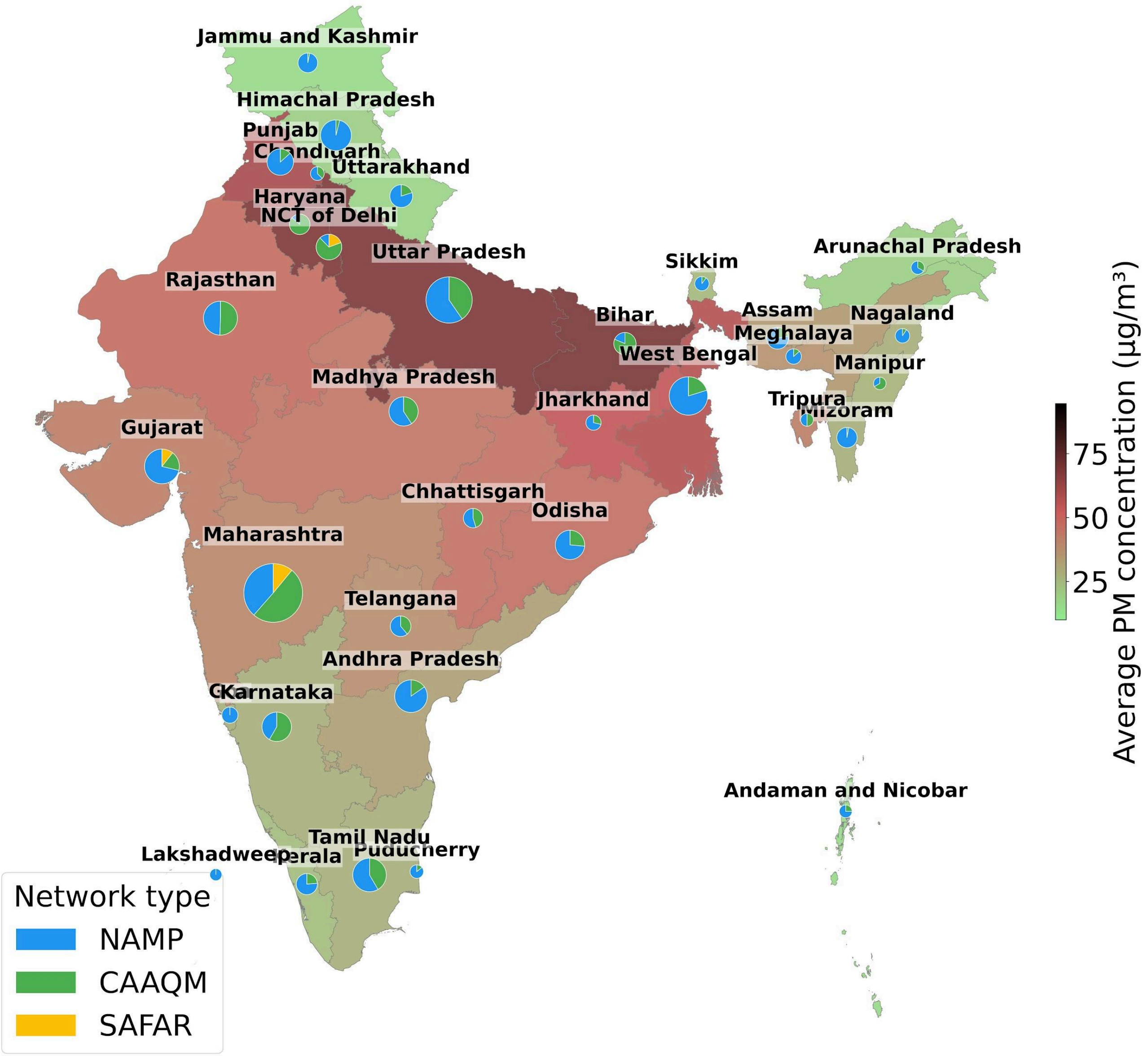
In addition to population-based criteria, IS 5182-14 (2000) explicitly links network design to pollution conditions and source characteristics. In practical terms, the standard implies denser monitoring in areas where elevated concentrations have been observed or are expected due to major emission sources (e.g., transport corridors or industrial clusters), as well as in locations with higher potential exposure risks.

Pollution and air-monitoring cover by states

At the state level, a moderate positive correlation is observed between the number of monitoring stations and average $PM_{2.5}$ concentrations ($r = 0.406$). This fact is actually interesting, reflecting the way budgets are allocated giving priority to more polluted cities and regions. Although this relationship is not strong, it is statistically meaningful and indicates that more polluted states tend, on average, to host a larger number of monitoring stations.



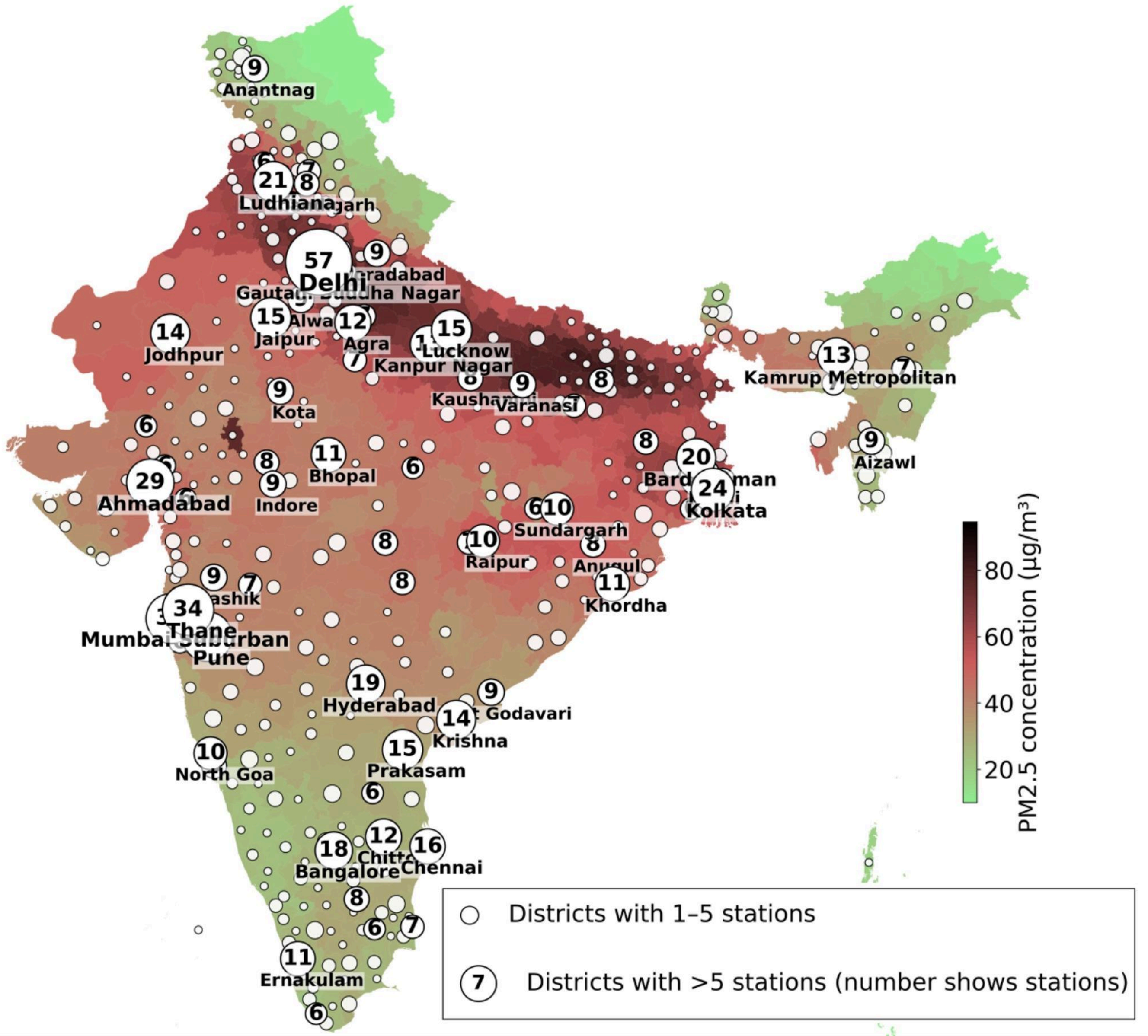
When viewed against the normative framework of the standard, we observe partial alignment with a pollution-prioritization principle. Several of the most polluted parts of the Indo-Gangetic Plain—most notably the NCT of Delhi and neighboring high-$PM_{2.5}$ states/territories such as Haryana, Punjab/Chandigarh, Uttar Pradesh, Bihar, and West Bengal—also exhibit comparatively larger monitoring footprints. This expansion has been driven primarily by the growth of automated CAAQM stations, complemented by NAMP coverage. The observed configuration suggests that historically high-pollution regions have, to some extent, received priority in station deployment, although the alignment with pollution-based planning criteria remains incomplete rather than systematic.



Air quality monitoring network and p.m. 2.5 levels across Indian states

Pollution and air-monitoring cover by districts

To analyze the relationship between station availability and pollution levels, district-level correlations were calculated using average $PM_{2.5}$ concentrations. For this analysis, two types of exclusions were applied. First, the territory of Delhi was removed, since its monitoring density and administrative structure differ from other districts. Second, all districts without any monitoring stations were excluded, because their absence of data would prevent any meaningful comparison between pollution levels and the number of stations.

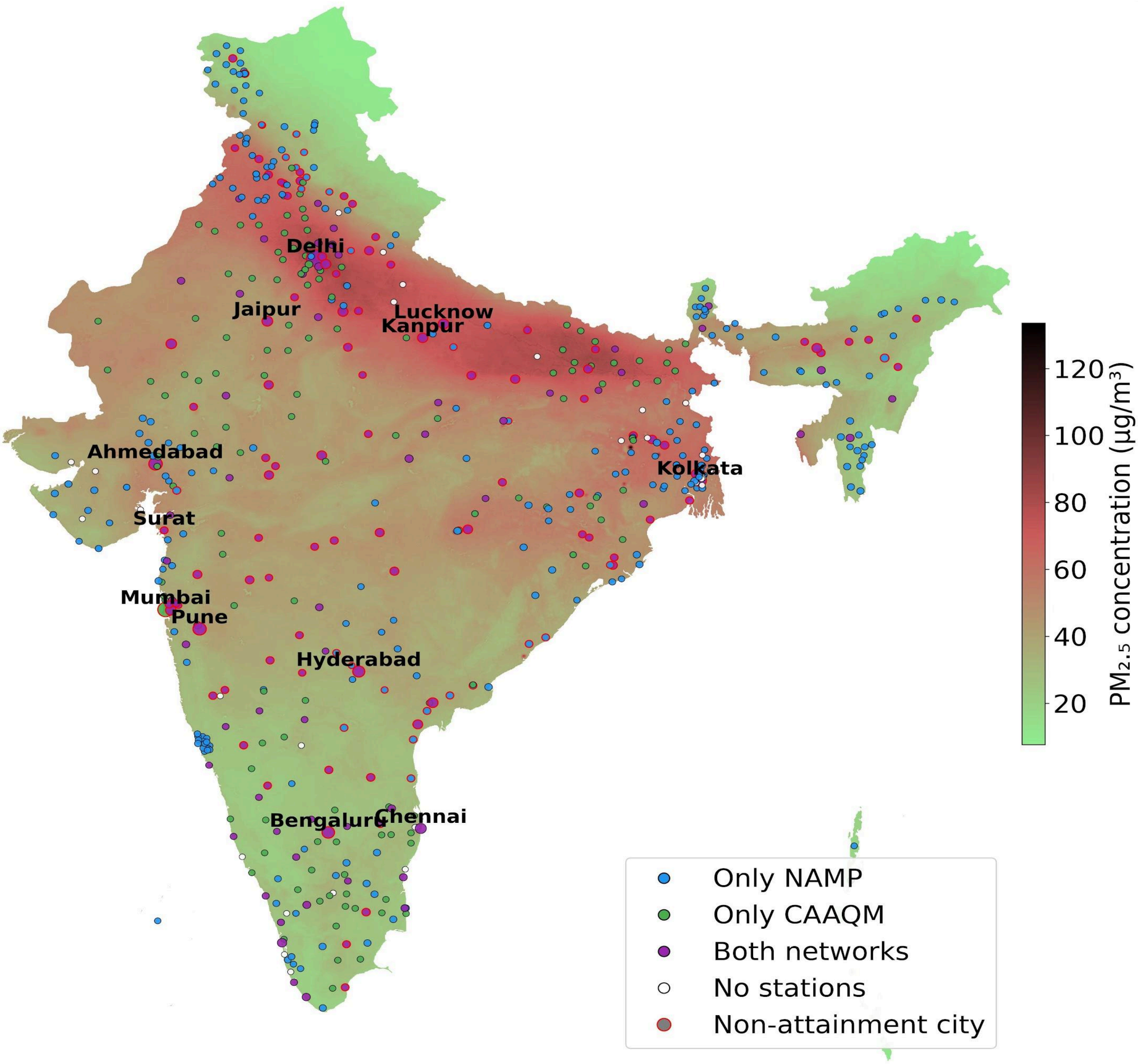


Monitoring stations per district and pollution p.m. 2.5

The spatial district-level map illustrates the same pattern: districts with elevated $PM_{2.5}$ concentrations are present both in areas with numerous stations and in areas with only small monitoring networks. Conversely, several districts with relatively low pollution levels operate extensive monitoring infrastructures.

Pollution and air-monitoring coverage by cities

A large number of highly polluted cities across the Indo-Gangetic Plain lack automatic monitoring altogether, and many non-attainment cities operate no stations of any kind. In contrast, major metropolitan areas — such as Delhi, Mumbai, Bengaluru, Chennai, Hyderabad and Kolkata — benefit from denser coverage, including automatic stations. The map illustrates regional gaps in real-time monitoring, particularly in areas with the highest long-term $PM_{2.5}$ exposure.



Cities with and without Stations on PM2.5 Pollution Map

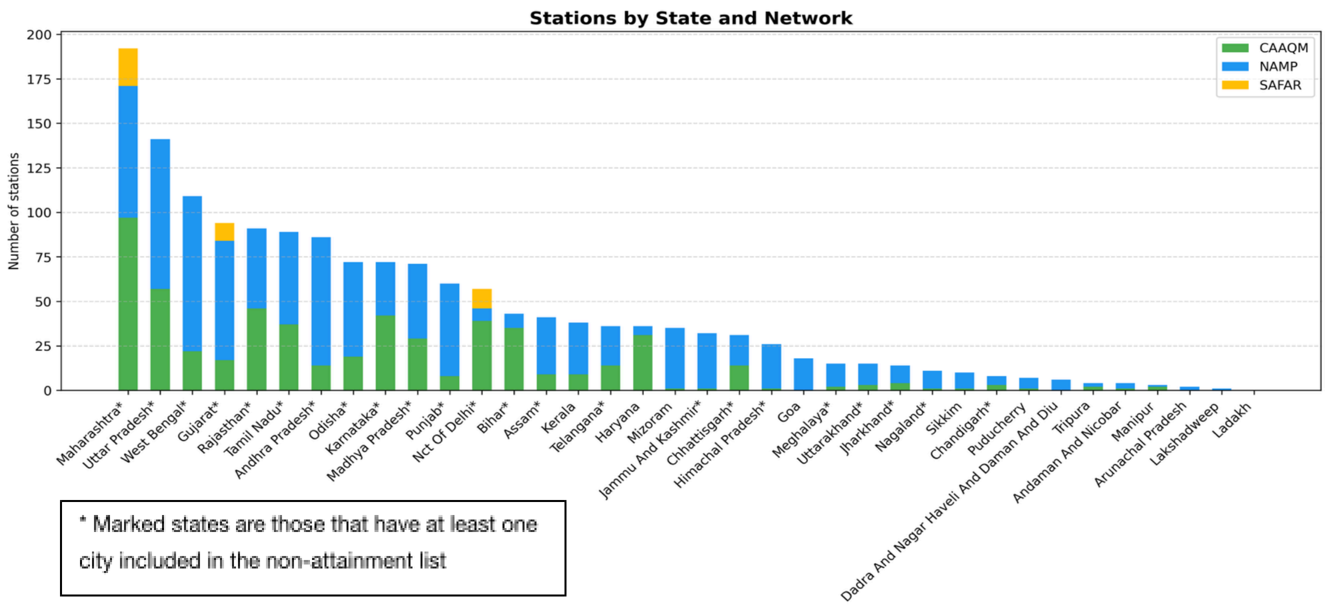
Part of this observational gap may be linked to topographic and logistical constraints: hilly terrain, low urban density, and the absence of major transport corridors in certain areas complicate the deployment and maintenance of monitoring infrastructure.

Nonetheless, given the concentration of industrial activity, the lack of coverage here represents a significant blind spot in the national air quality network.

Such localization of networks allows detailed tracking of pollution hotspots but provides little information about regional transport and diffusion of pollutants — a key factor for assessing the broader impact of urban emissions.

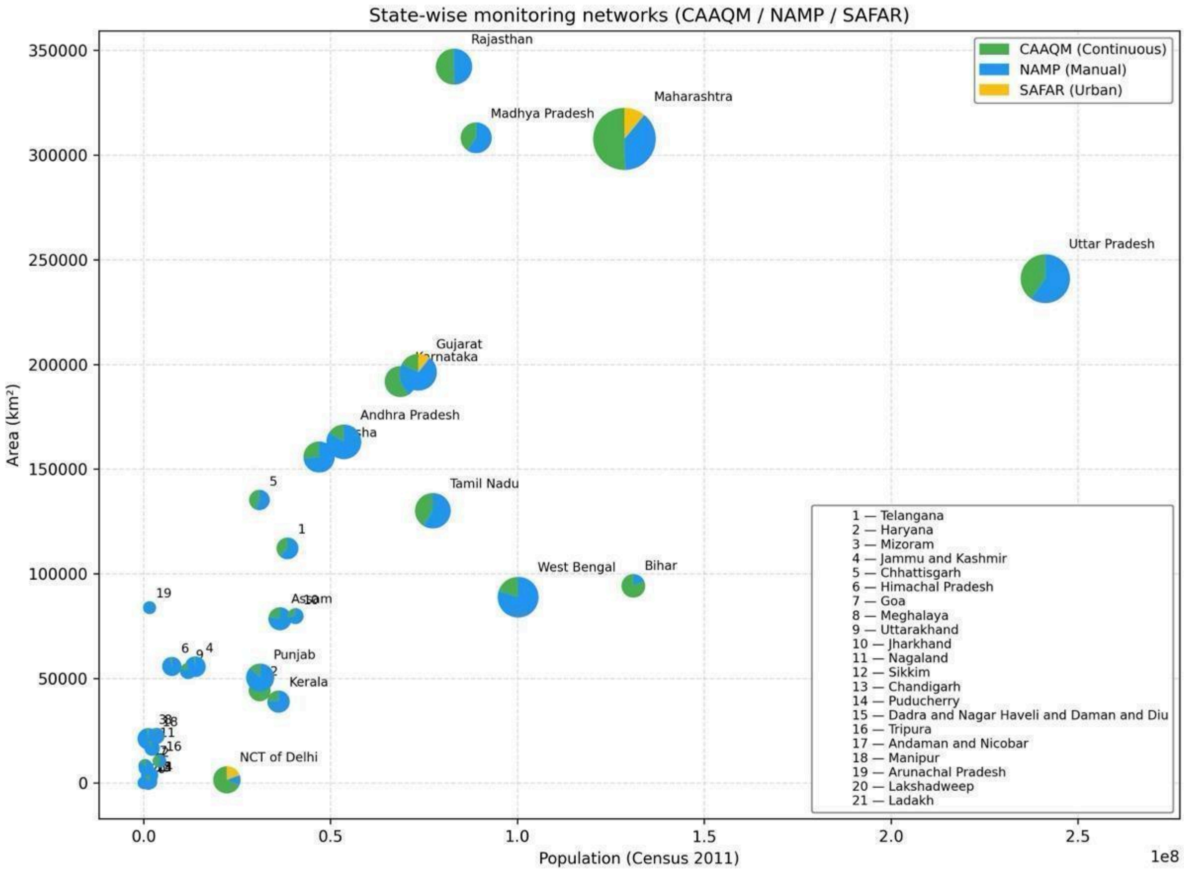
State-level coverage

According to the latest data, the states of Maharashtra, Uttar Pradesh, and West Bengal have the most extensive air quality monitoring networks in India, each hosting over 100 active stations across all monitoring programmes.



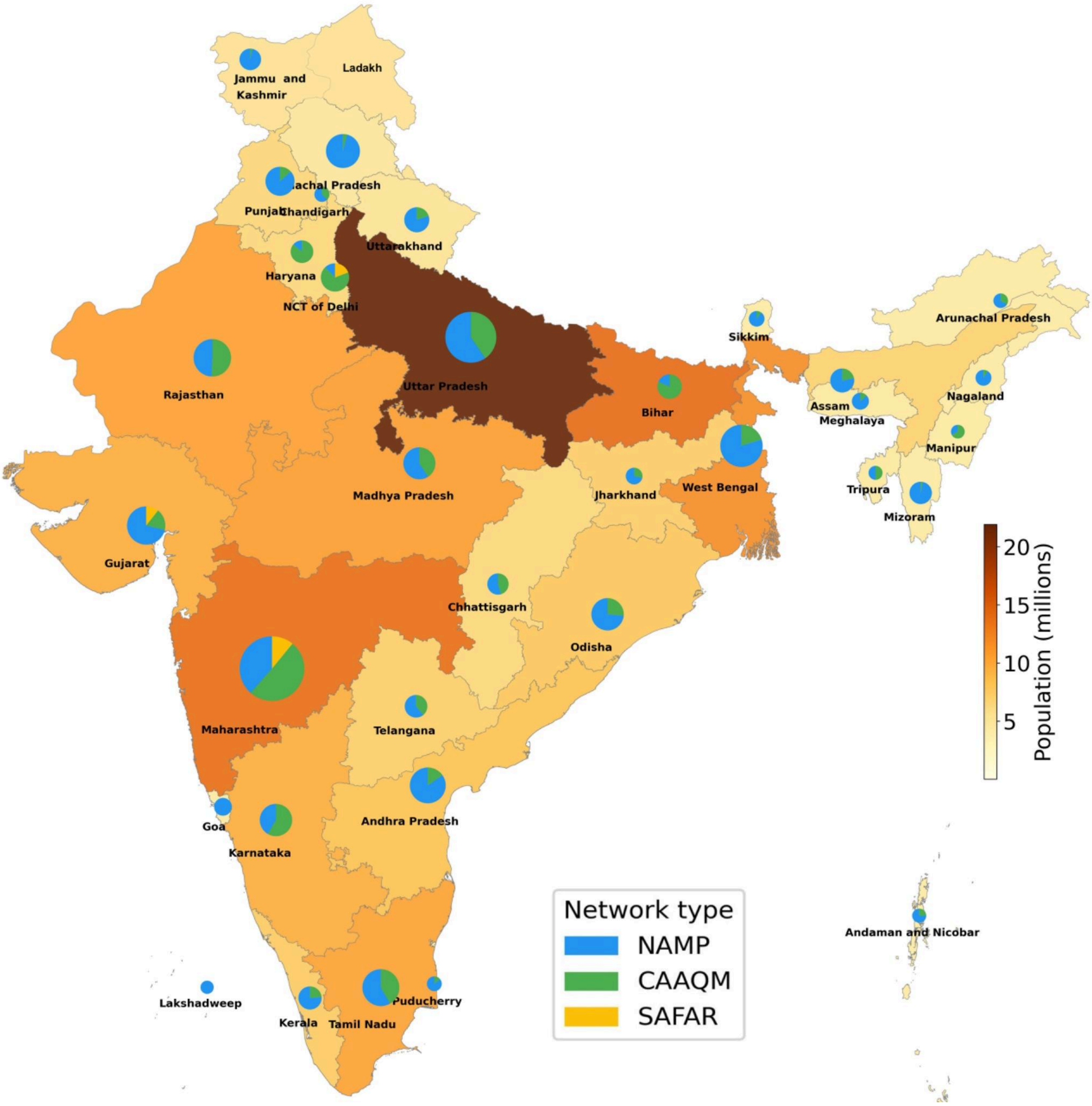
Several states maintain a substantial CAAQM network yet rely only minimally on NAMP. Examples include Delhi and several high-density urban territories where continuous monitoring predominates. These areas have strong real-time coverage but comparatively fewer manual sampling points.

Some states — such as Goa (which recorded approximately 5.45 million tourist arrivals in the first half of 2025 [12]), Arunachal Pradesh, Lakshadweep, and Dadra & Nagar Haveli and Daman & Diu — operate manual stations only, without any CAAQM or SAFAR presence. This leaves them without real-time data despite having at least basic observational capacity, and in Goa's case as a major tourist destination, access to operational air quality monitoring is particularly important.



Larger Indian states generally host more monitoring stations and maintain networks of different types, but there are exceptions. For example, Rajasthan and Madhya Pradesh cover vast areas yet their monitoring density remains moderate.

The most developed and diverse networks — combining CAAQM, NAMP, and SAFAR — are found in NCT of Delhi, Maharashtra and Uttar Pradesh, followed by West Bengal, which stands out despite its relatively small area. Several medium-sized states — Tamil Nadu, Gujarat, Karnataka, Andhra Pradesh, Odisha, and Punjab — also maintain balanced coverage.

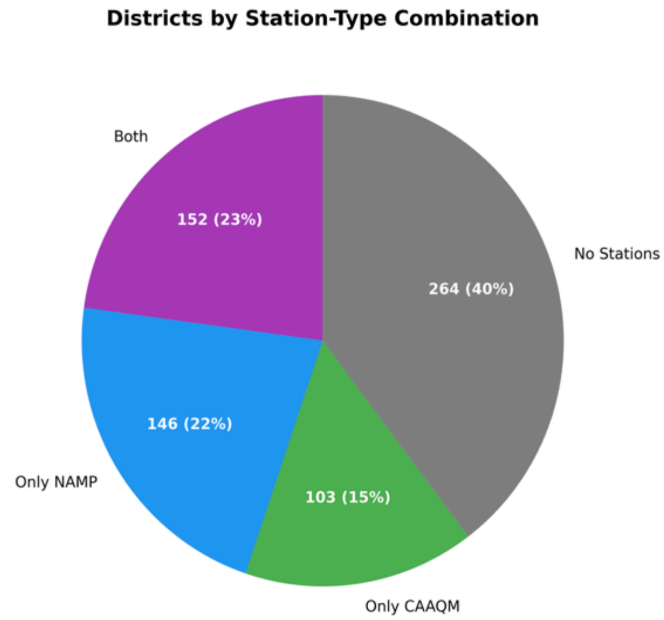


Air quality monitoring networks by population Indian states

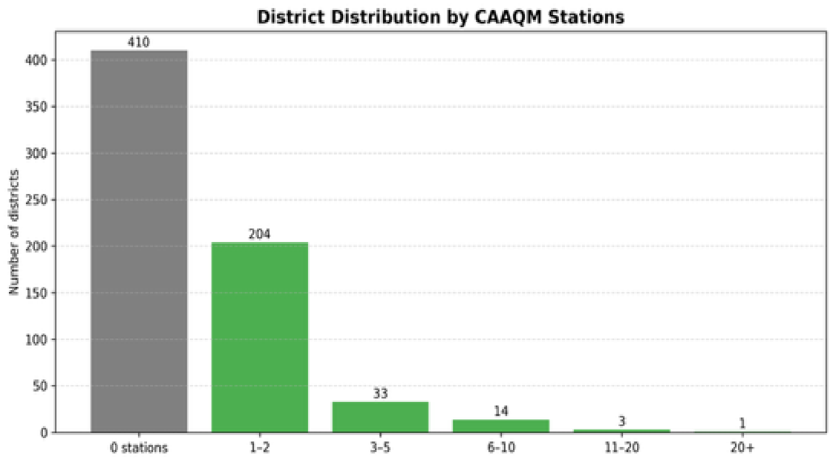
Ladakh remains the only major administrative unit with no stations of any network. Its geographic isolation and low population density contribute to this gap. The least equipped regions are Lakshadweep and Arunachal Pradesh, each having only one or two NAMP stations and no continuous monitoring. This limited coverage leaves large geographic and demographic areas without real-time air quality information.

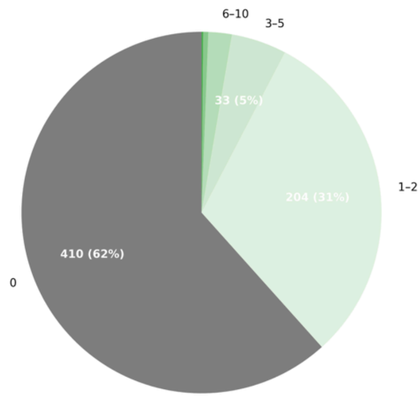
District-level coverage

Analysis of station distribution at a finer scale of administrative division shows that a substantial share of districts (about 40%) remains without any monitoring infrastructure. A total of 146 districts (22%) are equipped only with NAMP stations, while 103 districts (15%) have only CAAQM stations. Another 152 districts (23%) combine both types of monitoring, meaning they operate at least one station from each network.

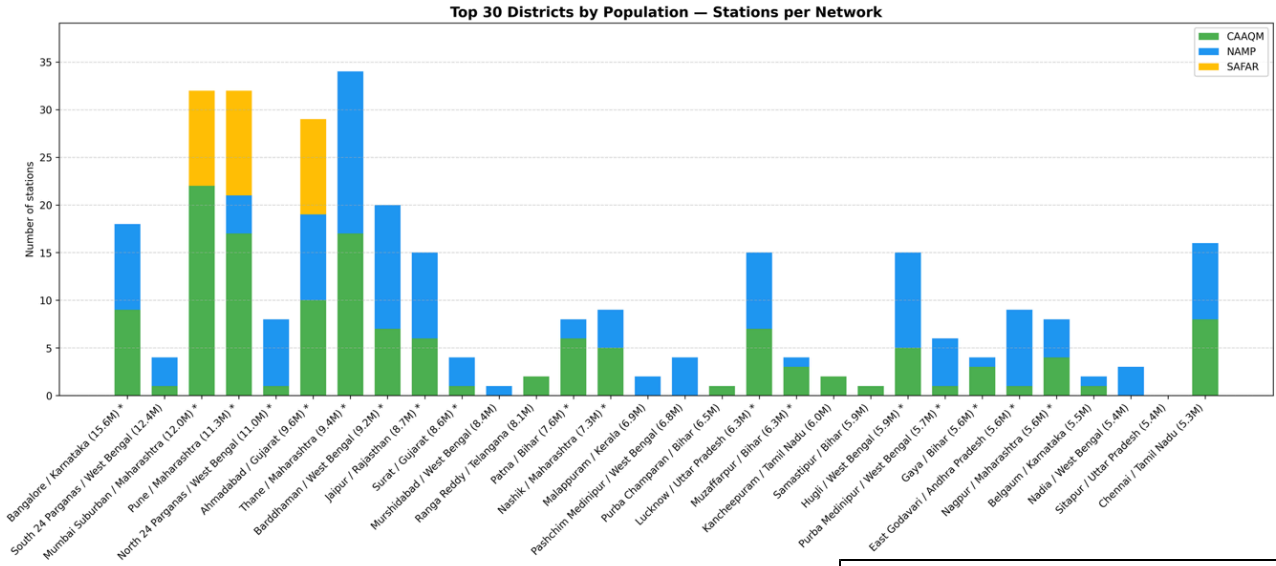


410 districts (62%) do not have CAAQM stations. The majority of monitored districts host only one or two automatic stations. For CAAQM, 204 districts fall into the 1–2 station range, and only a small number exceed five stations.



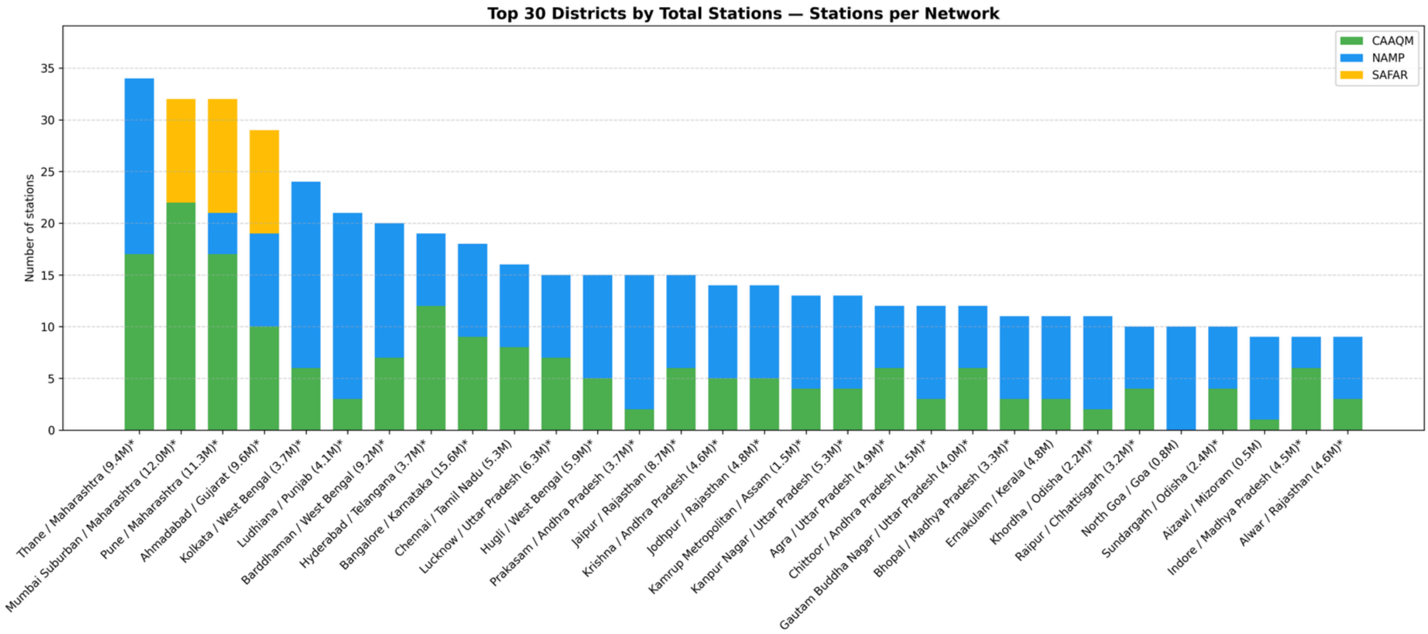


Among India's 30 most populated districts, the distribution of monitoring infrastructure remains highly uneven.

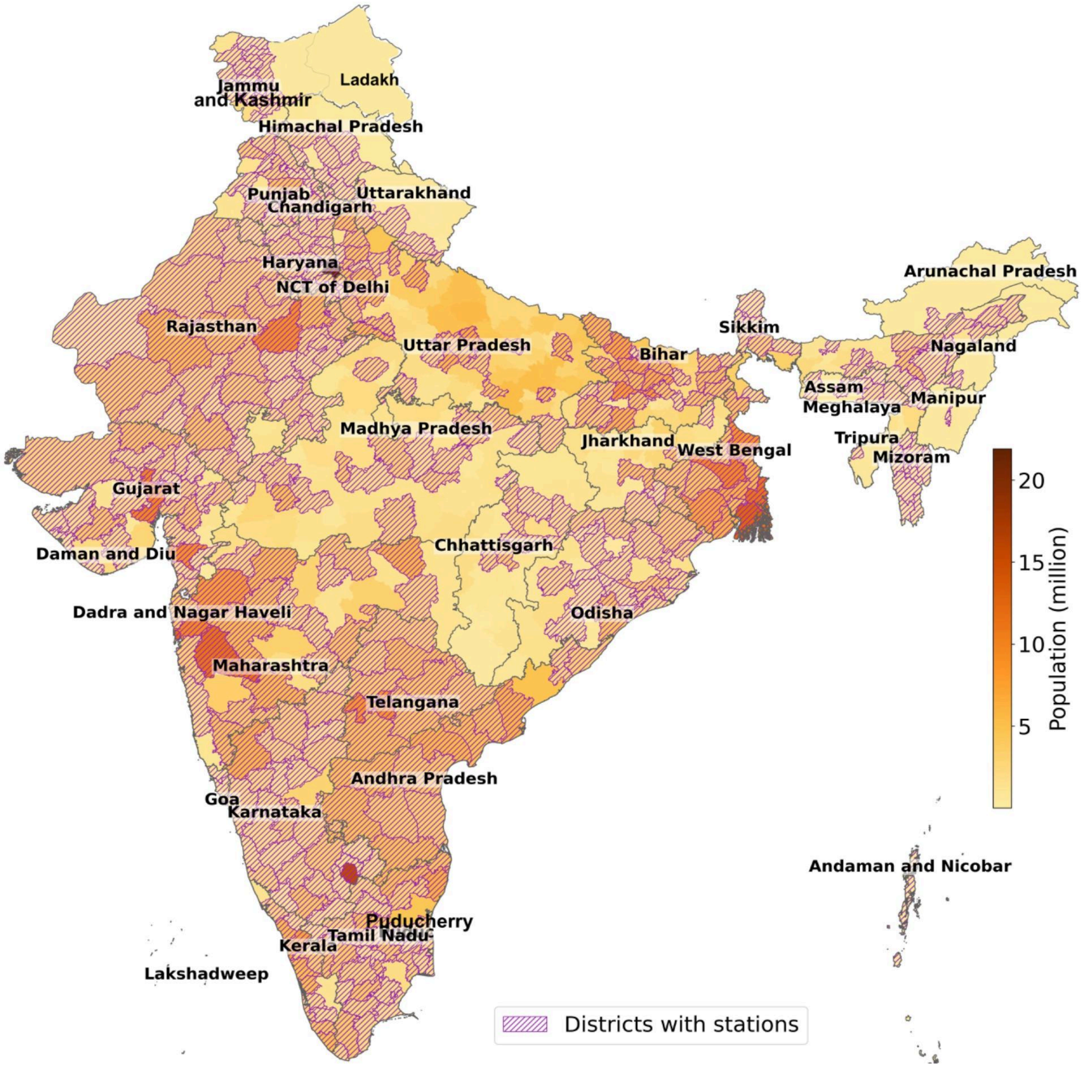


* Marked districts are those that have at least one city included in the non-attainment list

Several of India's most populous districts — including South and North 24 Parganas (West Bengal), Patna (Bihar), Murshidabad (West Bengal), Ranga Reddy (Telangana), and Nashik (Maharashtra) — host between five and thirteen million residents but have only limited monitoring infrastructure. In many of these districts, CAAQM stations are absent or greatly underrepresented. Examples include Murshidabad and Aurangabad (Bihar), which rely solely on NAMP, while districts such as Surat (Gujarat), Jaipur (Rajasthan), and Nagpur (Maharashtra) also lack sufficient CAAQM coverage despite dense urban development. Additional high-population districts like Hooghly (West Bengal) and Guntur (Andhra Pradesh) either have no stations or only one operational site, creating clear gaps in real-time monitoring, especially along state boundaries.

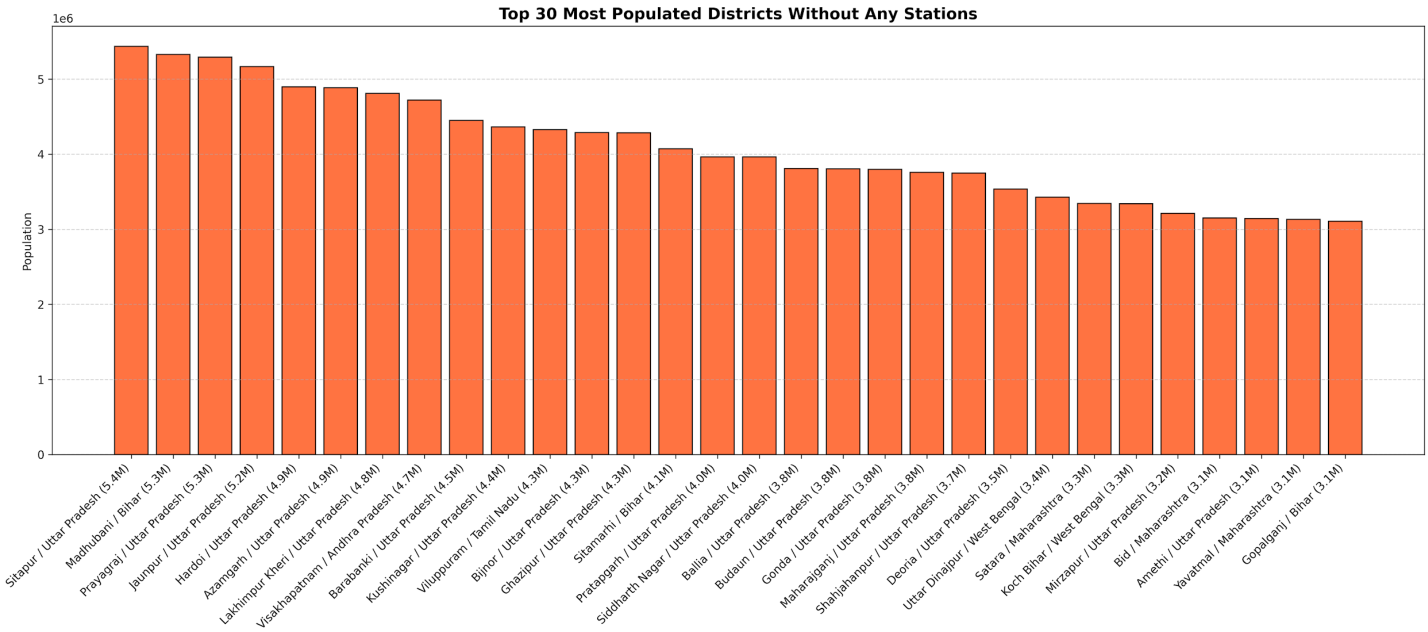


The top of the ranking is dominated by highly urbanized and industrial districts such as Thane, Mumbai Suburban, Pune, Ahmedabad, and Kolkata, where the presence of multiple automatic CAAQM stations drives the highest overall monitoring capacity.



Population by District + all stations Coverage + States

In contrast, several mid-sized districts appear in the top-30 primarily due to large numbers of manual NAMP stations rather than automatic coverage. This highlights a structural imbalance: the districts with the strongest monitoring infrastructure are those with substantial CAAQM deployments, while many other areas depend almost entirely on manual networks.



Several of the most populated districts without any monitoring stations — including Sitapur (Uttar Pradesh), Madhubani (Bihar), Allahabad (Uttar Pradesh), Jaunpur (Uttar Pradesh), and Visakhapatnam (Andhra Pradesh) — each host more than 4 to 5 million residents but remain outside the national monitoring framework.

City-level Coverage

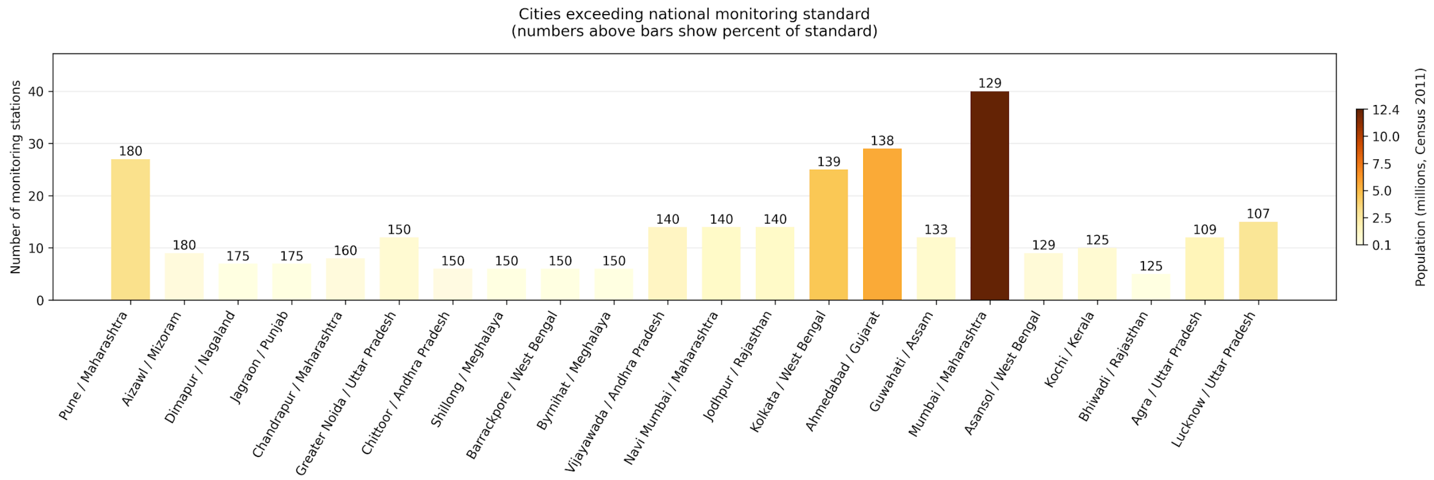
Air quality monitoring stations are located in 558 cities, towns, and villages across India, with populations ranging from 136 residents to about 17 million according to the 2011 Census of India. Among them, 140 locations host only CAAQM (Continuous Ambient Air Quality Monitoring) stations, 260 have only NAMP (National Air Monitoring Programme) stations, and 158 include both networks.

For the purposes of further analysis, we examined the spatial distribution of monitored locations and identified cases where smaller towns or villages are functionally integrated into the agglomerations of larger cities. Where such relationships were evident, monitoring sites located in satellite towns and peri-urban communities were grouped with the corresponding metropolitan areas.

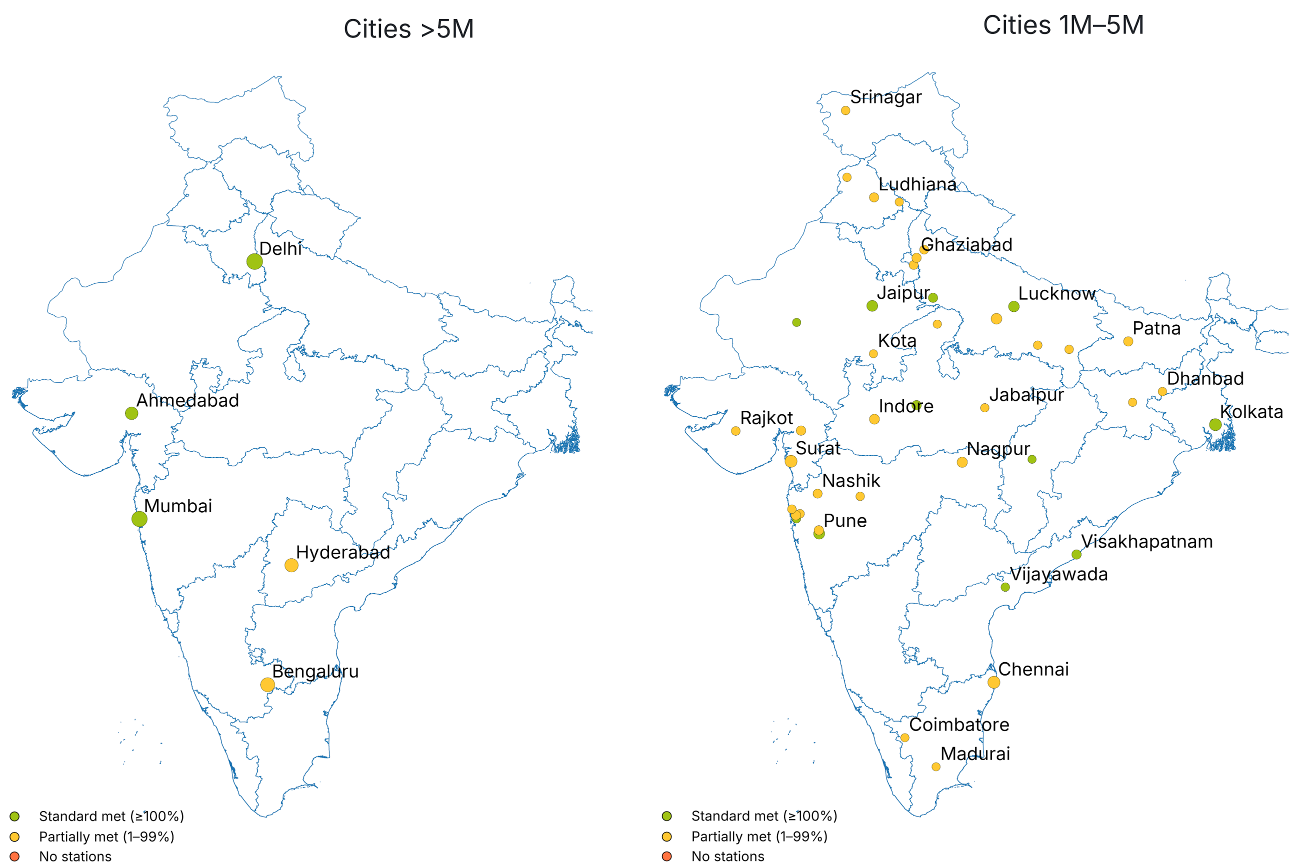
Even after this aggregation, however, a small number of monitoring stations remain located in very small villages. This is particularly characteristic of sparsely populated regions and geographically remote areas. In two cases, NAMP stations are situated in villages with fewer than 1,000 residents that are not part of any urban agglomeration: Gulaba (Himachal Pradesh) and Dawki (Meghalaya). In addition, 35 monitored towns and villages have populations between 1,000 and 10,000 inhabitants. Most of these locations are served by the manual NAMP monitoring network.

Coverage by national standard

It is important to note that the Indian standard IS 5182-14 does not distinguish between towns and villages with populations below 100,000. According to the population-based recommendations included in the standard, communities in this category should ideally be equipped with at least four monitoring stations.

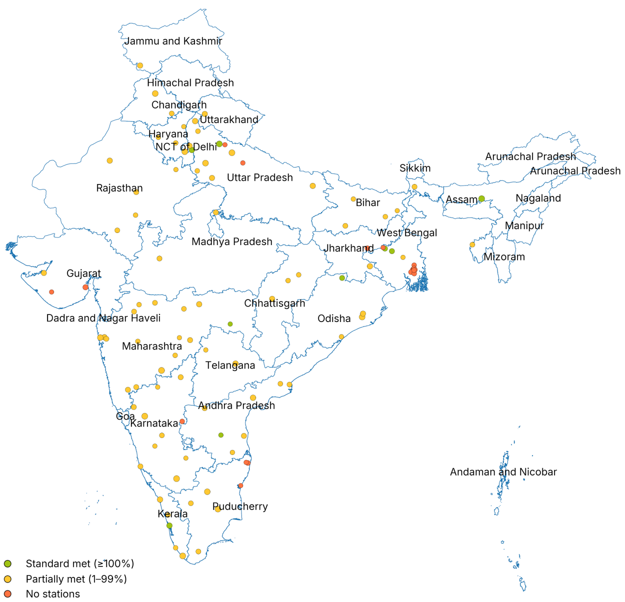


Using the population counts from the 2011 Census of India, we evaluated whether the number of operating monitoring stations in each city meets the minimum levels recommended in the national guidelines. The analysis shows that a number of cities not only satisfy the minimum requirement but exceed it.

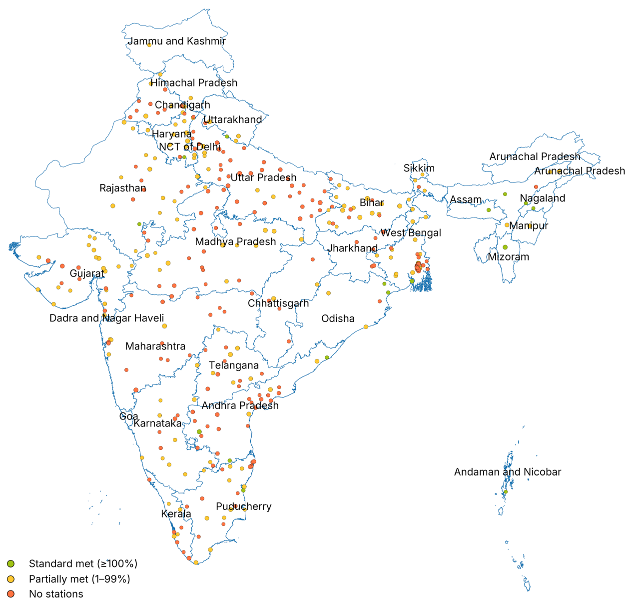


For example, in the national capital Delhi, the monitoring network exceeds the minimum standard by roughly 50%. A similar pattern can be observed in several other cities, where the number of stations is also noticeably higher than the minimum required for cities of comparable population size. It is important to note that the standard specifies only the minimum number of stations. Therefore, exceeding the recommended level does not indicate a deviation from the guidelines but rather reflects that the monitoring network operates with a certain margin above the required baseline. In some cases, relatively high compliance percentages are also related to the fact that smaller cities have lower minimum requirements.

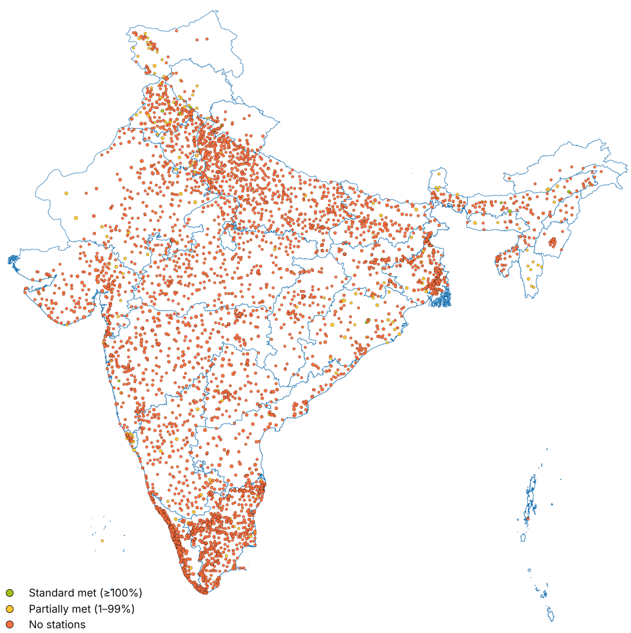
Cities 300k–1M



Cities 100k–300k



Cities 10k–100k



When Indian cities are grouped by population size, a clear general pattern emerges. Larger cities tend, on average, to have better monitoring coverage than smaller ones. In major metropolitan areas and large urban agglomerations the minimum standards are more frequently met or exceeded, whereas among small and medium-sized cities there are significantly more settlements where the standard is only partially met or not met at all.

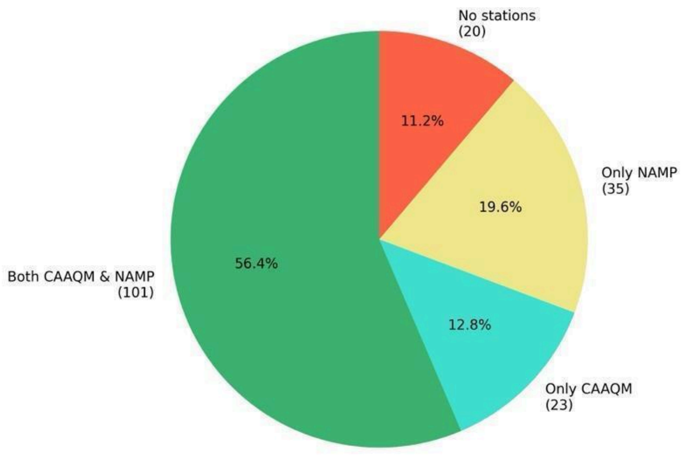
Population-Based Classification of Urban Areas

In the subsequent analysis, we therefore focus primarily on places with populations above 10,000 inhabitants. For analytical purposes, these locations are grouped into population-based categories: small towns (10,000–100,000 residents), medium-sized cities (100,000–300,000 residents), large cities (300,000–1 million residents), and major cities (1–5 million residents). The largest population category (>5 million residents) includes only four cities in our dataset — Delhi, Mumbai, Bengaluru, and Hyderabad — which are therefore discussed individually in the analysis.

These thresholds are chosen to reflect the structure of the dataset and the observed distribution of monitoring coverage across Indian cities.

For each population group, we compare the minimum number of monitoring stations recommended by the standard with the actual monitoring infrastructure currently in operation.

To assess the monitoring coverage of larger urban areas, this dataset was supplemented with cities and urban agglomerations with populations exceeding 300,000 residents, based on the United Nations World Urbanization Prospects (WUP), Urban Agglomerations Database [10].



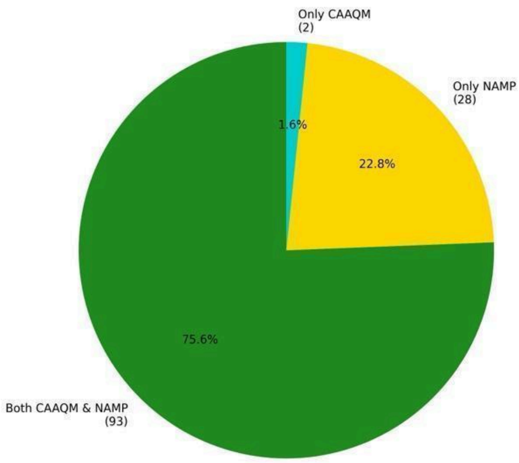
Station coverage in agglomerations >300k population (WUP 2025)

Approximately 11% of urban agglomerations with populations exceeding 300,000, as listed in the United Nations *World Urbanization Prospects* (Urban Agglomerations Database), do not have a single air quality monitoring station. However, when considering cities above the same population threshold based on the older 2011 Census of India, nearly all of them have at least one monitoring station from one of the networks.

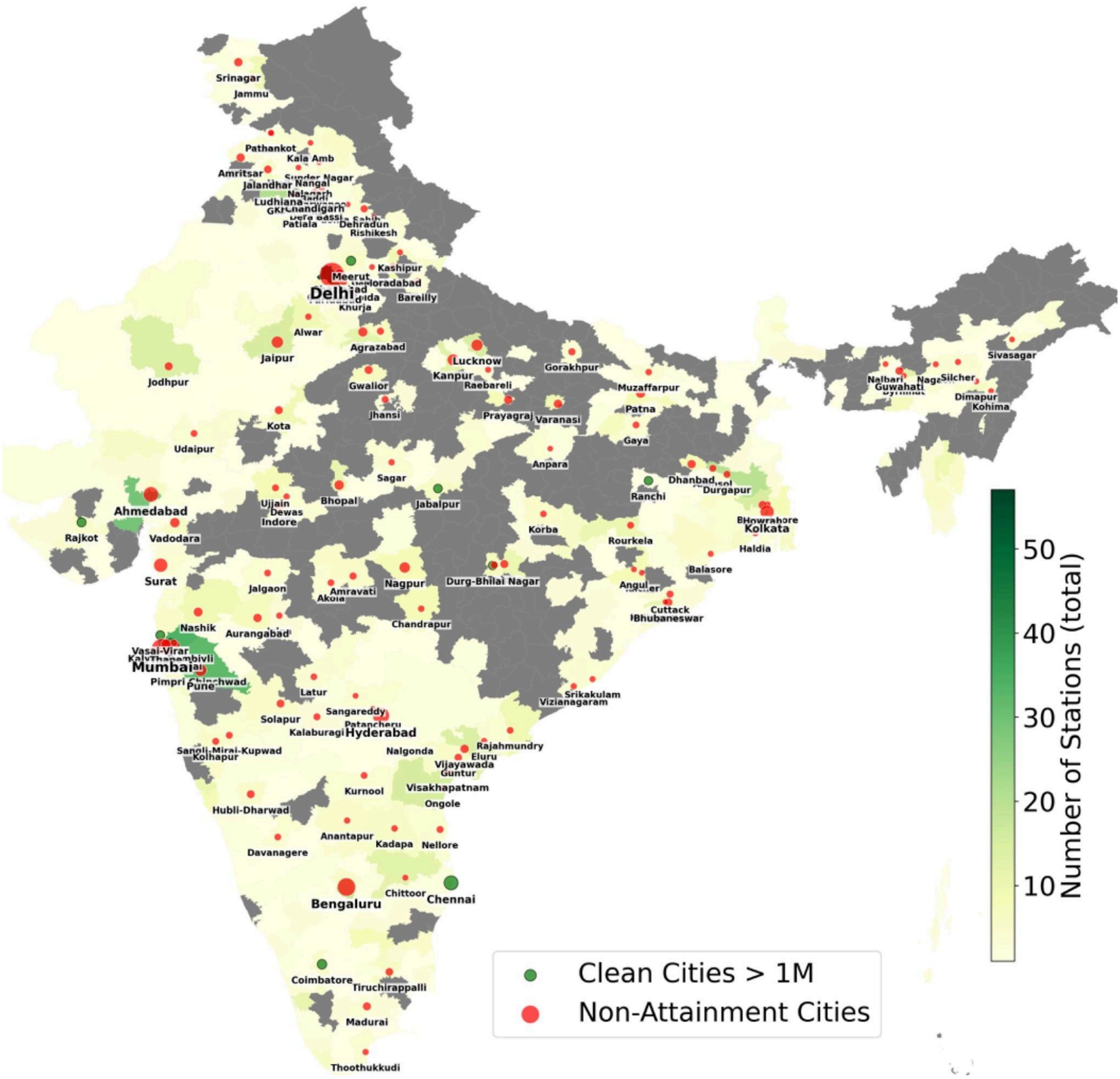
This discrepancy is primarily driven by differences in population estimates and delineation approaches. In this study, the UN Urban Agglomerations Database was used with population estimates for 2025, which are based on modelled and projected growth, whereas the 2011 Census reflects official population counts from an earlier reference year. As a result, some settlements are classified as large agglomerations in the UN dataset due to projected growth, while their population remains below the 300,000 threshold according to the older census data.

Non-Attainment Cities and Policy Priorities

To better understand the priorities of India's national air quality policies, it is important to consider the list of «non-attainment cities» published by the Central Pollution Control Board (CPCB) under the National Clean Air Programme (NCAP).



This list identifies cities that did not meet the National Ambient Air Quality Standards (NAAQS) over several consecutive years.

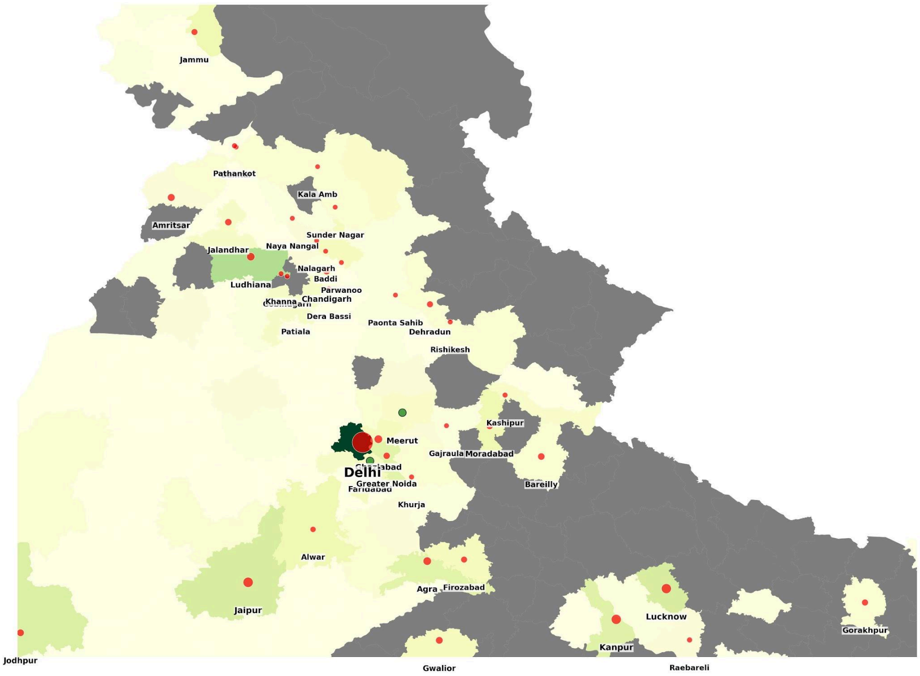


District Station Coverage and Non-Attainment Cities

As of 2025, it includes 131 cities: 123 cities where systematic exceedances of pollution norms were recorded, and 8 million-plus agglomerations that were added to ensure comprehensive coverage of major urban areas, even if their air quality generally remains within acceptable limits. The official list is publicly available on the CPCB website.

Among the 123 non-attainment cities officially identified under the National Clean Air Programme (NCAP), every city has at least one active air quality monitoring station. Most of them are covered by both national networks: 93 cities (75.6%) host CAAQM and NAMP stations simultaneously. Another 28 cities (22.8%) rely solely on manual NAMP monitoring, while 2 cities (1.6%) have only CAAQM stations.

The distribution of non-attainment cities across India closely follows the existing network of monitoring stations — yet their surroundings often remain unobserved.

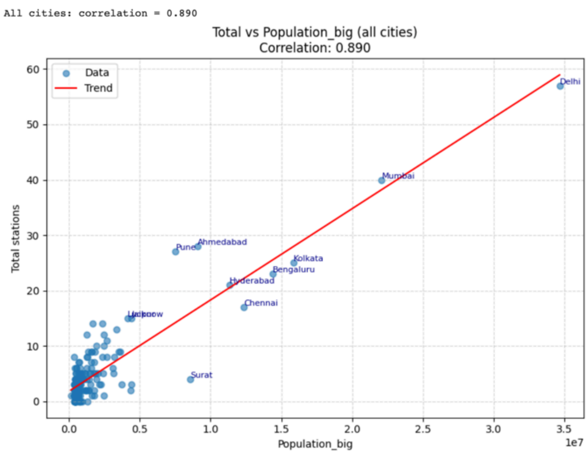


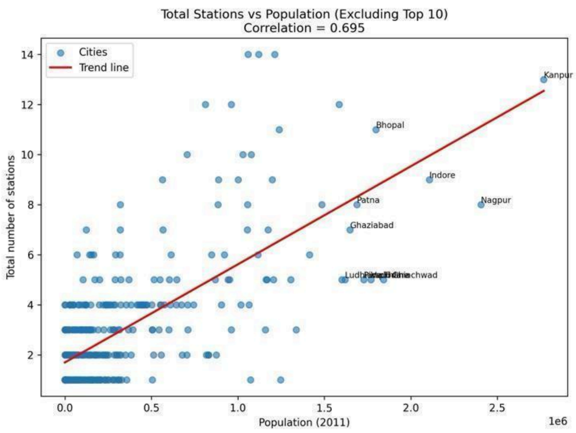
North-West India: Non-Attainment and Clean Cities (Zoomed View)

Most polluted cities are located within dense clusters of measurement coverage, forming visible “observation enclaves” where air monitoring stations operate within or near municipal boundaries. However, the grey, unmonitored areas between these clusters reveal large territories where air quality is not systematically measured.

Coverage Relative to Population

When all agglomerations with over 300,000 inhabitants are included, the correlation between population and number of monitoring stations reaches r = 0.89, indicating a very strong relationship.

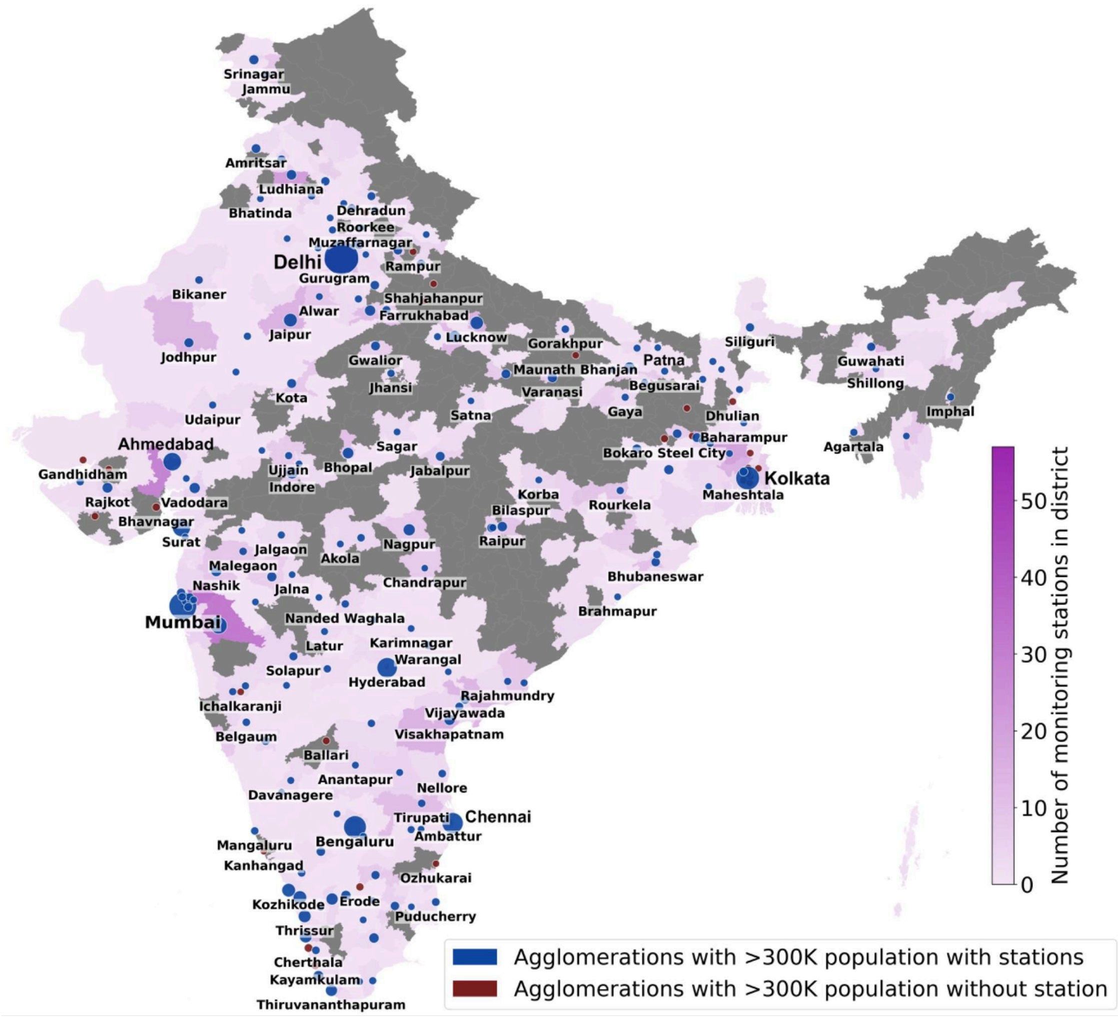




However, this trend is to a high degree entirely driven by a handful of population giants — Delhi, Mumbai, Kolkata, Bengaluru, Chennai, Hyderabad, Ahmedabad, and Pune — which dominate both population size and monitoring capacity. Once these top 10 cities are excluded, the correlation decreases to r = 0.695, revealing a somewhat weaker, though still significant positive, association.

Monitoring Coverage in Large Urban Agglomerations

Most of India's 300K-plus cities are already covered by at least one air quality monitoring station. In this representative group, the number of stations grows only slowly with population. Several examples stand out: Lucknow, Kanpur, and Jodhpur show relatively high coverage, while comparably large cities such as Kozhikode, Malappuram, Thrissur, or Coimbatore remain under-monitored.

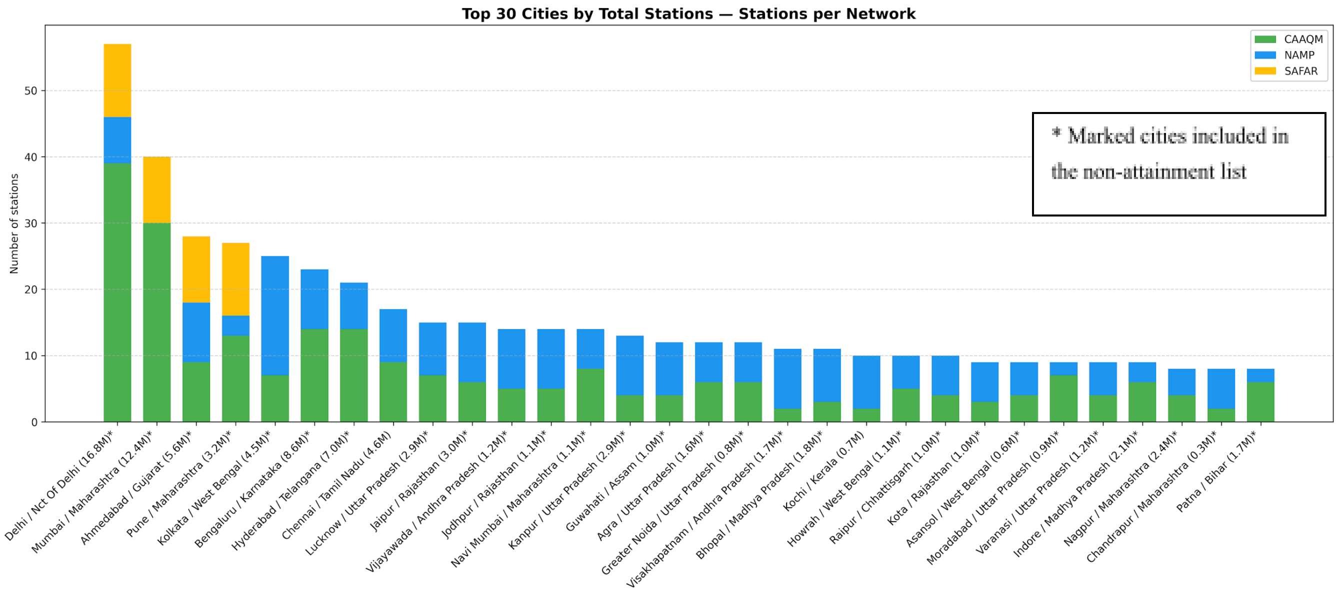


Agglomerations with >300K population with or without stations

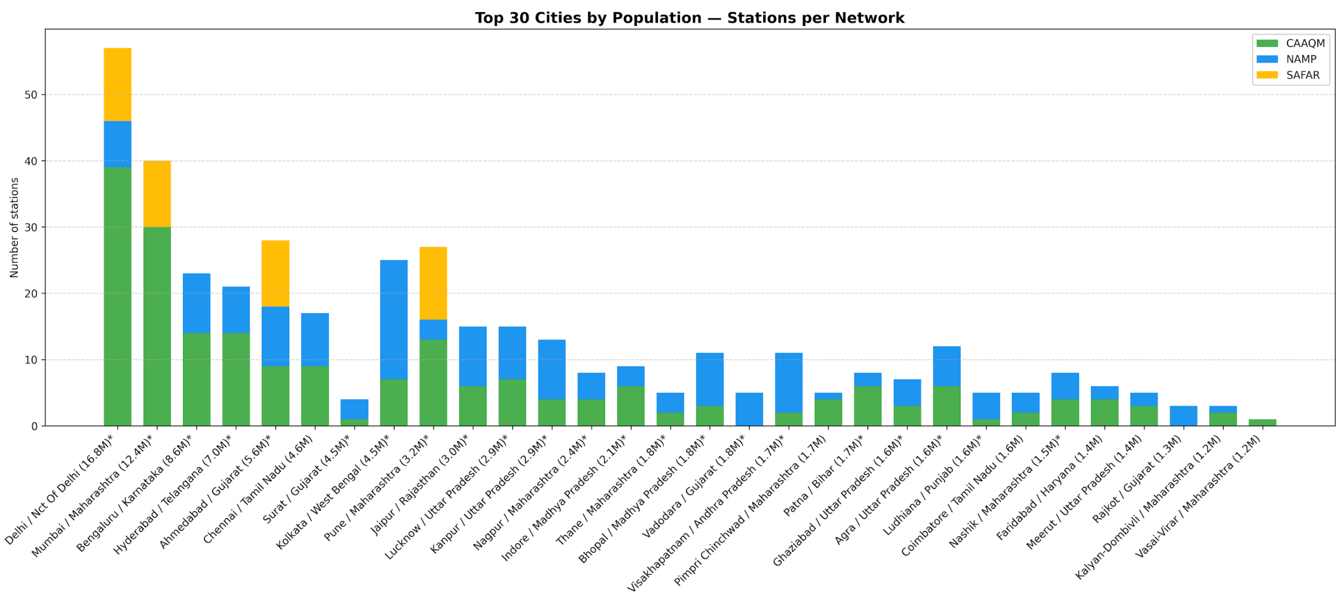
For the vast majority of urban areas, monitoring expansion does not yet scale proportionally with demographic size. And roughly one in ten agglomerations (11%) still lacks any government-operated air quality monitoring site, which highlights regional gaps even within the most urbanized areas.

Leading Cities by Monitoring Coverage and Population

The dominance of Delhi and Mumbai is evident — they host several dozen stations across all three national networks. In Mumbai, the monitoring strategy places a particular emphasis on automatic measurements. Manual sites are present mainly in Navi Mumbai, reflecting the city's preference for continuous real-time observations in its core urban areas. Other well-equipped metropolitan areas include Ahmedabad, Bengaluru, Hyderabad, and Chennai, each operating between 15 and 30 stations.

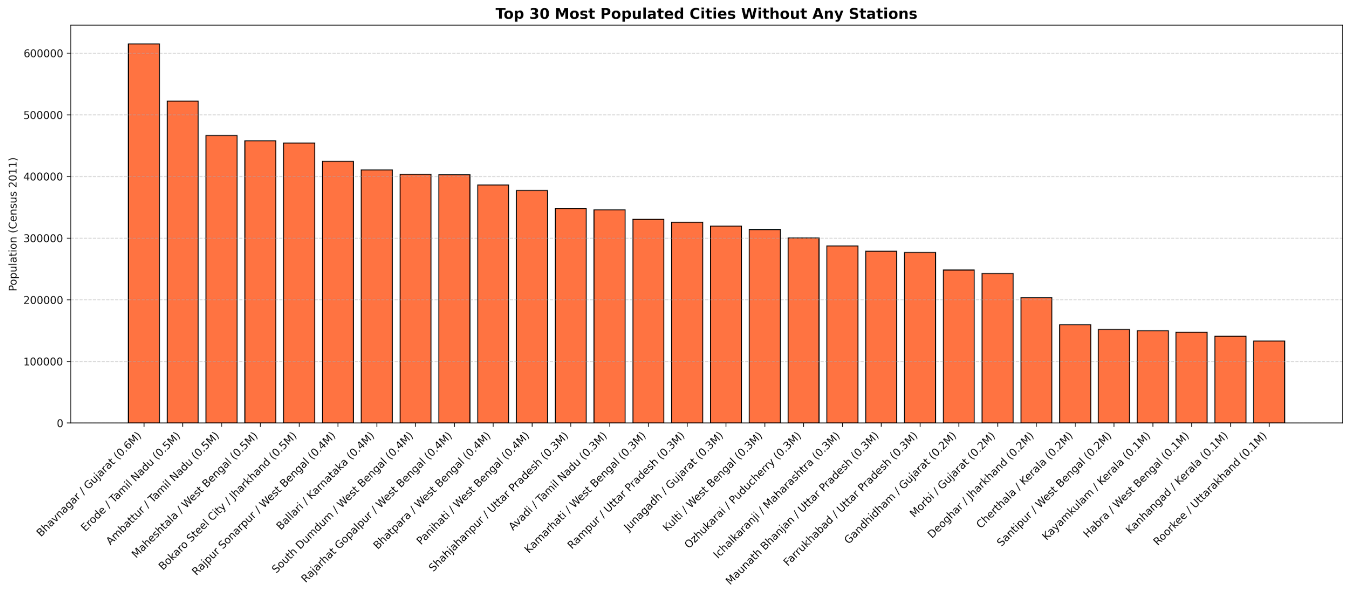


However, the population ranking shows considerable imbalance: cities like Surat, Vadodara, Rajkot, and Dombivli — each with populations above one million — operate fewer than five monitoring sites. In many of these cases, automatic stations are limited or absent. Leaving cities with substantial industrial activity and dense urban development dependent primarily on manual observations.



Under-Monitored Cities

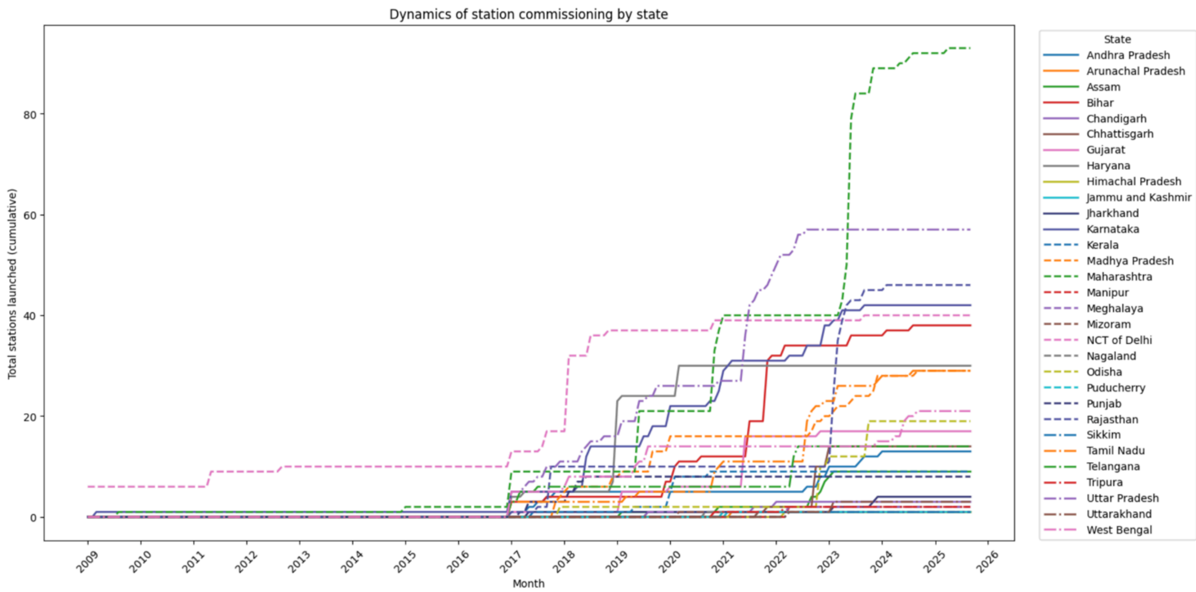
A number of fairly large cities with populations between 300,000 and 600,000 still lack any government-operated air quality monitoring infrastructure. Among the largest of these are Bhavnagar (Gujarat), Erode (Tamil Nadu), and Ambattur (Tamil Nadu), each with populations exceeding half a million in the 2011 Census.



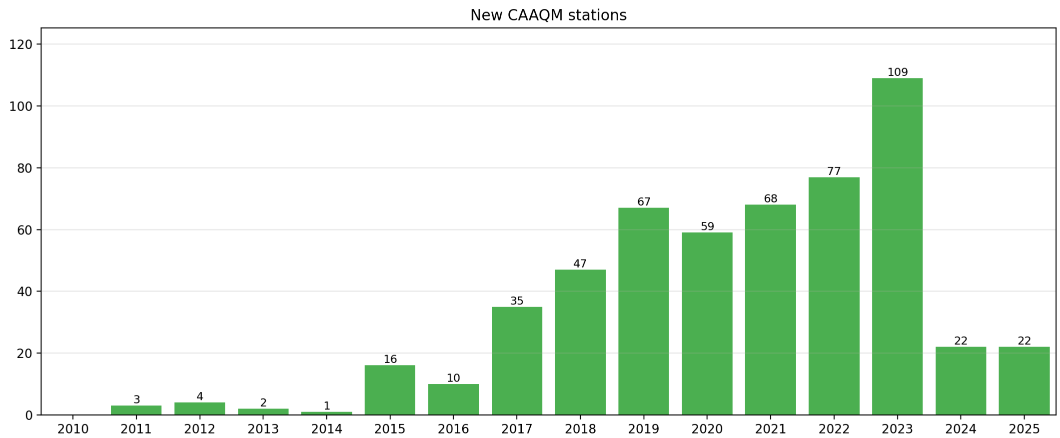
CAAQM Network: Coverage and Open Data

India's continuous air quality monitoring network has expanded steadily since the first CAAQM stations began reporting data in 2009. Over the past fifteen years, the system has grown to 562 operational stations distributed across 294 cities in 32 states and union territories. The network continues to develop, with new stations added each year and coverage gradually extending into additional urban and industrial regions.

Network Growth and Geographic Expansion



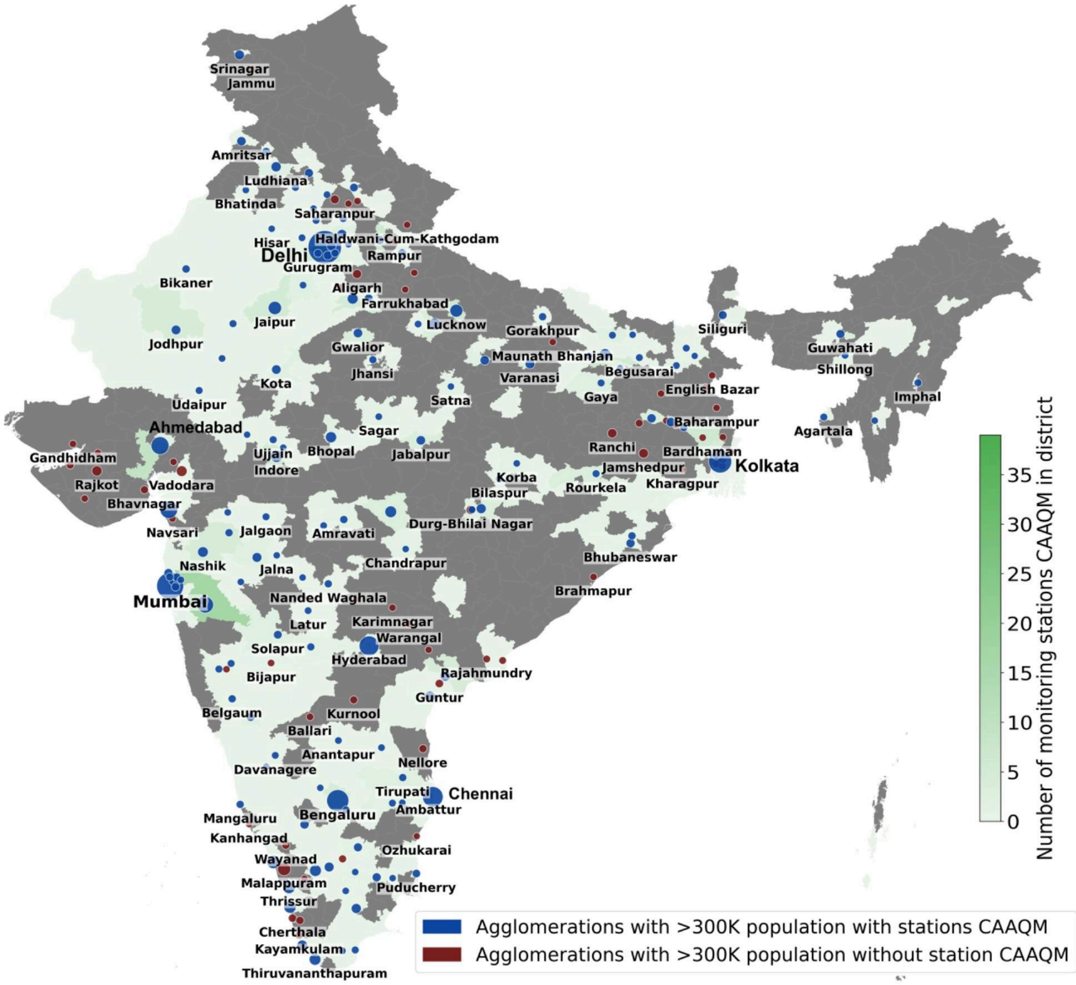
The years 2020–2023 stand out as the most active period of growth, with several states adding substantial numbers of new stations. Maharashtra shows the largest increase, rising from 34 stations in 2020 to 81 by 2023. Uttar Pradesh experienced a similarly rapid expansion, nearly doubling its count between 2020 and 2023. Rajasthan, Bihar, Madhya Pradesh, Karnataka, Tamil Nadu, and Haryana also registered marked year-on-year increases during this period.



By contrast, the years 2017–2019 saw only modest growth, with most states adding just one or two stations. Smaller northeastern and hill states remained largely unchanged throughout the entire period, with many maintaining one or zero stations year after year.

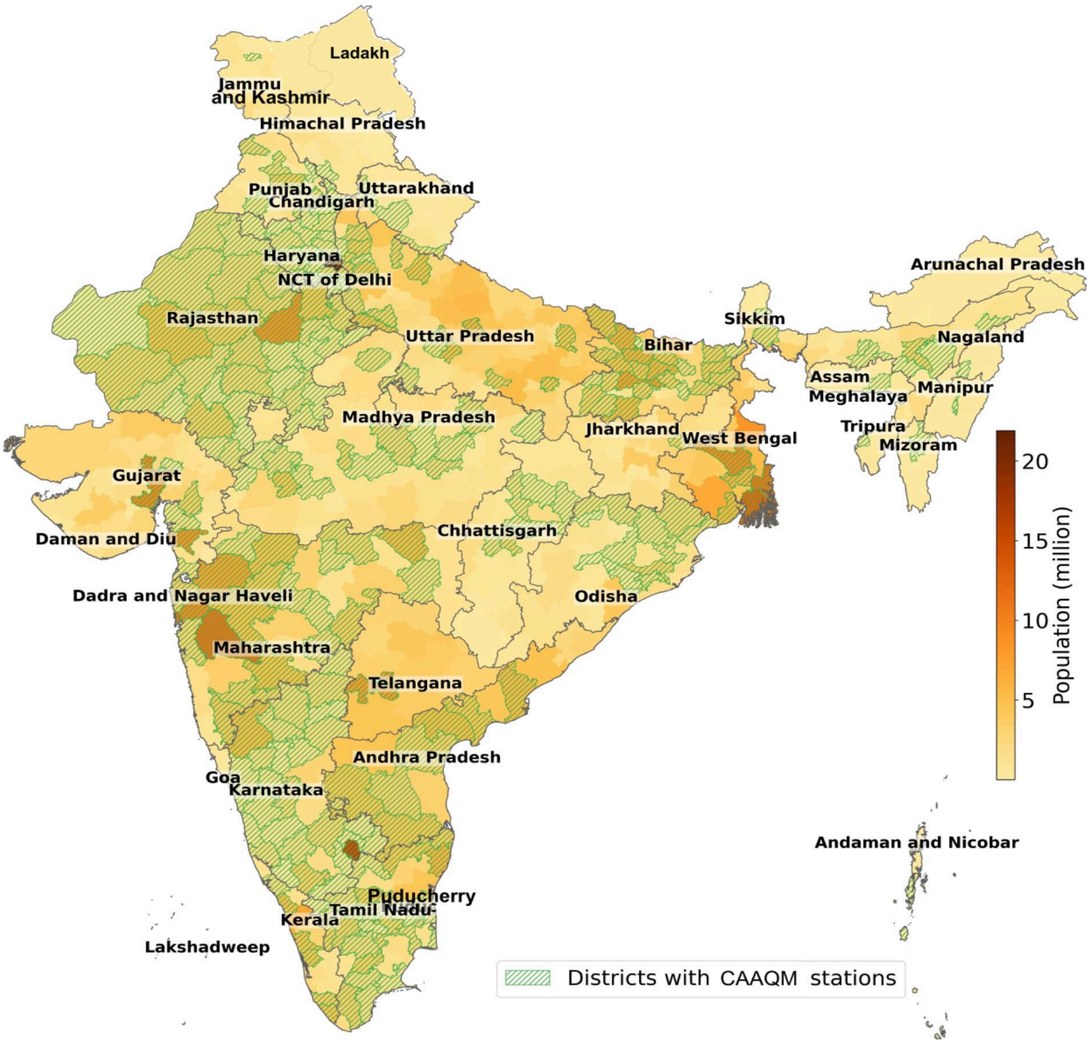
Uneven Distribution and Regional Gaps

Despite the expansion of the CAAQM network, significant gaps persist across India's urban landscape. Several densely populated regions—such as the periphery of Kolkata, the industrial belts of Gujarat, and coastal urban clusters in Tamil Nadu and Andhra Pradesh—still lack local continuous monitoring nodes. Many of the cities in these areas are major touristic, commercial or industrial hubs, yet remain dependent on manual or regional-level observations.

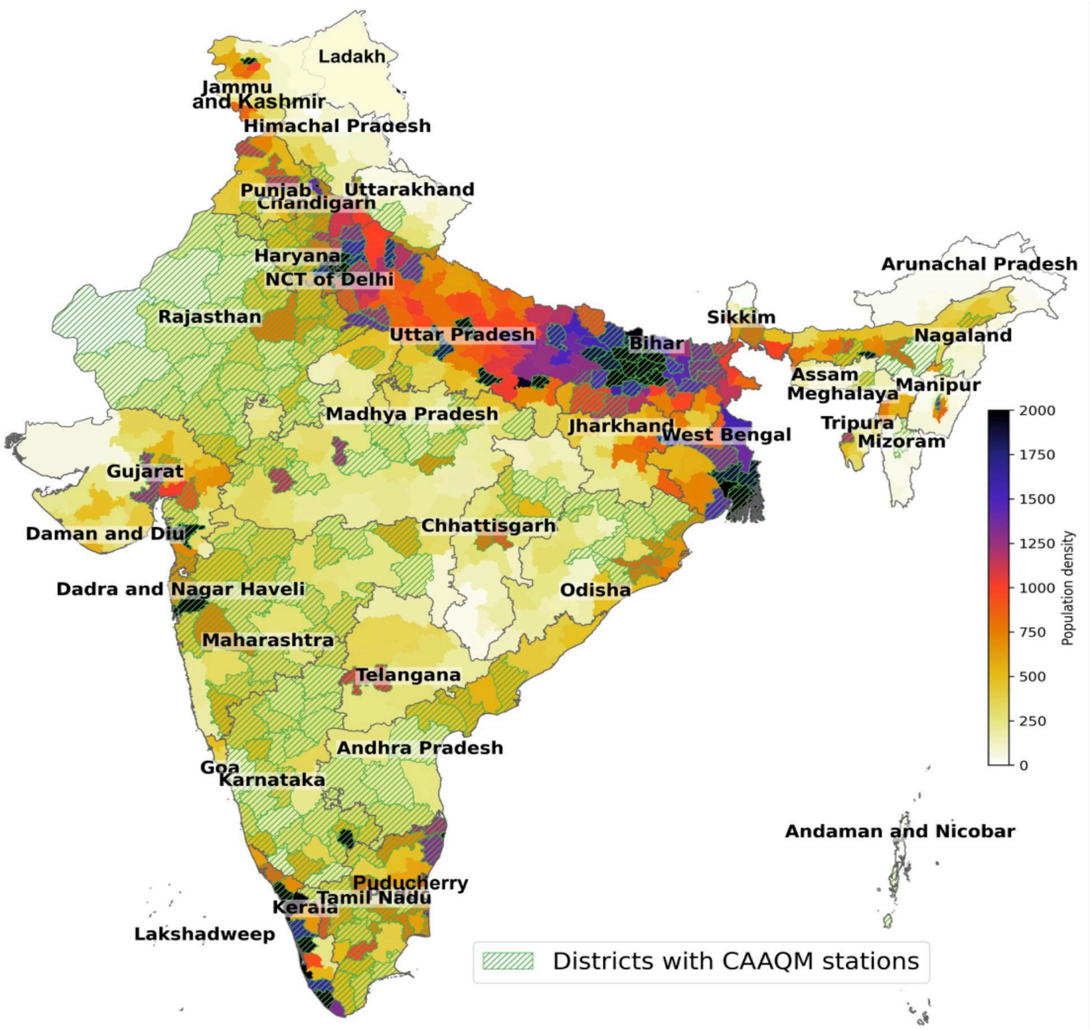


CAAQM Network Coverage by districts and agglomerations with >300K population

When districts are compared by total population, the largest population concentrations appear across the Indo-Gangetic Plain, parts of Maharashtra, Tamil Nadu, Karnataka, and Telangana. However, the deployment of continuous monitoring stations (CAAQM) shows a more selective pattern: many high-population districts host at least one automatic station, but coverage is far from universal. Stronger representation is evident in major metropolitan and industrial regions—such as Delhi, Mumbai, Pune, Ahmedabad, Hyderabad, Bengaluru, and Chennai—while numerous populous districts in Uttar Pradesh, Bihar, West Bengal, and Assam remain only partially covered. This confirms that population size alone has not been the primary driver of CAAQM deployment.

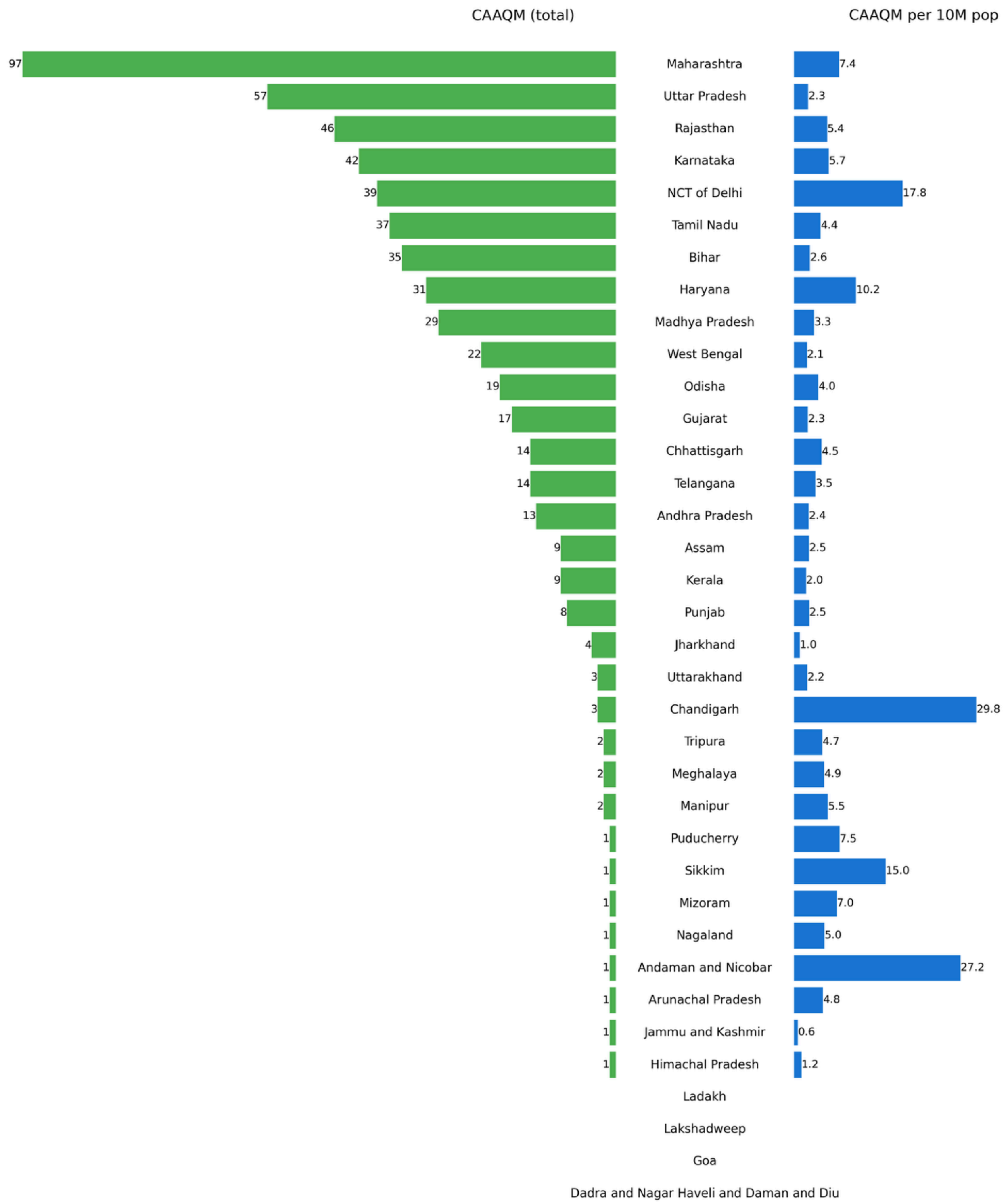


Population by District and CAAQM Coverage



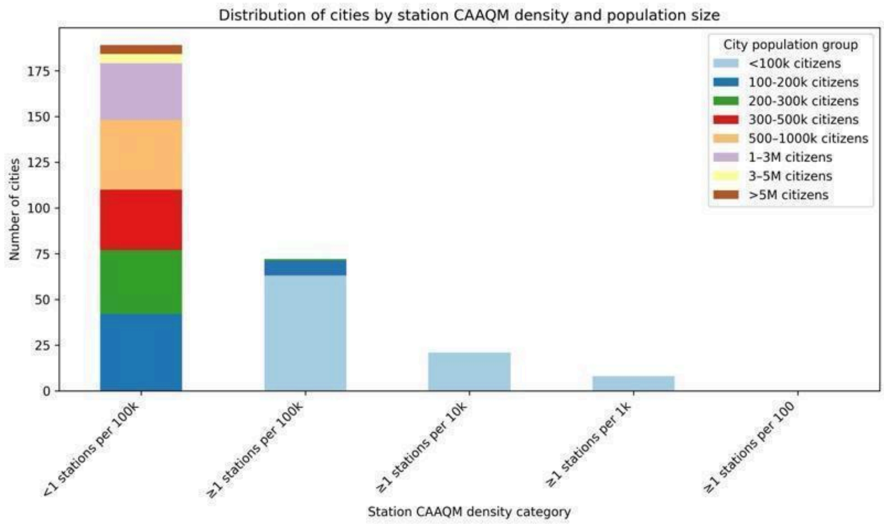
Population density by District and CAAQM Coverage

The picture shifts further when population density is considered. The densest sections of the Indo-Gangetic Plain — stretching through Uttar Pradesh, Bihar, and West Bengal — stand out as areas where demographic pressure is exceptionally high, yet continuous monitoring remains uneven and often limited to a few nodes. Additional dense clusters in coastal Tamil Nadu and central Kerala similarly exhibit inconsistent station presence. While several high-density urban areas are well instrumented, large portions of densely populated regions rely on sparse or non-local CAAQM coverage, indicating a gap between demographic concentration and automatic monitoring availability.



Ladakh, Lakshadweep, Goa, and Dadra and Nagar Haveli and Daman and Diu still remain without continuous air quality monitoring.

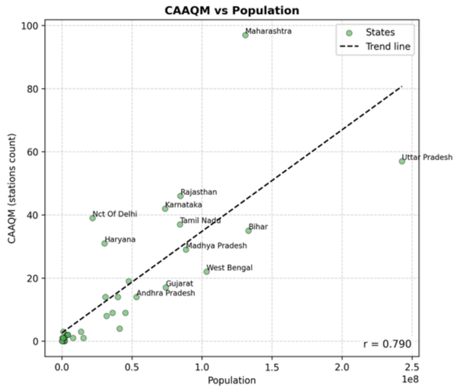
In the CAAQM network, continuous monitoring sites are concentrated in major cities, but their density remains very low relative to population.

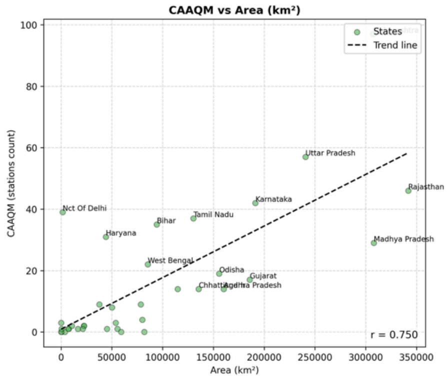


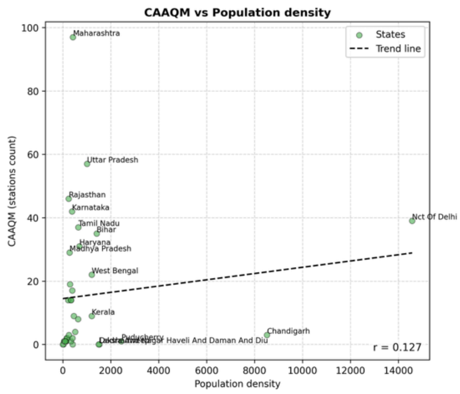
Among India's large cities with more than 300,000 inhabitants, the majority (56%) are covered by both monitoring networks but only about 13% have only continuous CAAQM stations.

Correlations with Demographic and Environmental Indicators

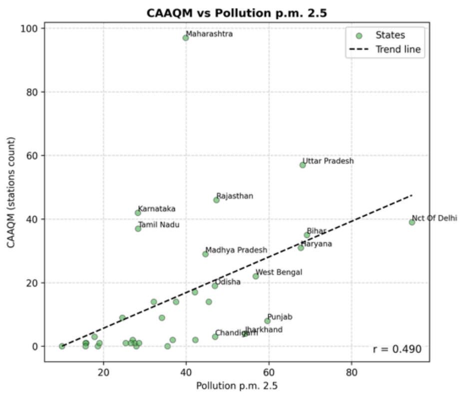
For CAAQM, the number of stations demonstrates a strong positive correlation with state area (r = 0.75) and an even stronger correlation with total population (r = 0.79), indicating that the deployment of continuous monitoring follows administrative scale and demographic weight rather than population density. No significant correlation is observed between CAAQM coverage and population density (r = 0.13), meaning that smaller, densely populated states are not necessarily better equipped. Maharashtra, Uttar Pradesh, and Delhi remain clear outliers, reflecting targeted expansion of urban networks and regulatory infrastructure.







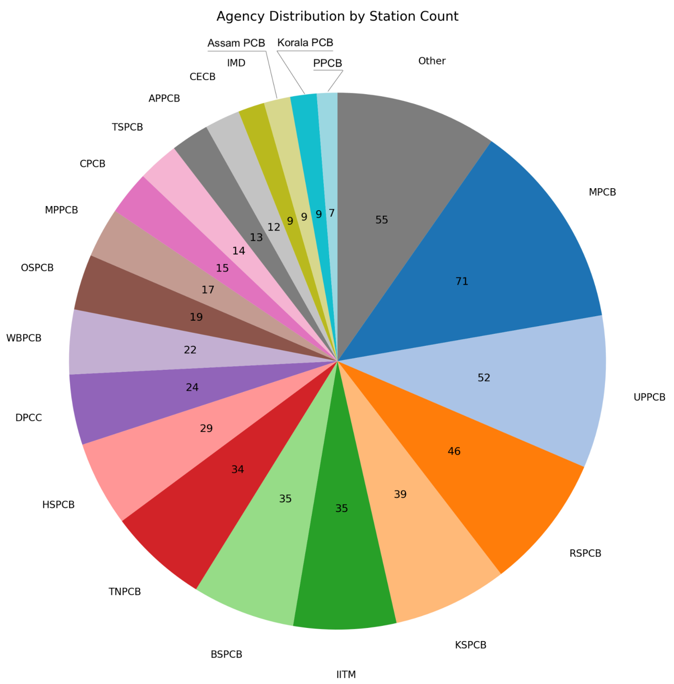
When examining pollution levels at the state scale, certain patterns begin to emerge. States with persistently higher $PM_{2.5}$ concentrations tend to host a larger number of monitoring stations across different networks. This trend becomes clearer when focusing specifically on the automatic CAAQM network. In the CAAQM plot (r = 0.490), heavily polluted regions such as Delhi, Punjab, Haryana, Bihar, and Uttar Pradesh show a more noticeable increase in the number of automatic stations, indicating that areas with historically elevated $PM_{2.5}$ levels have received more instruments for continuous real-time monitoring.

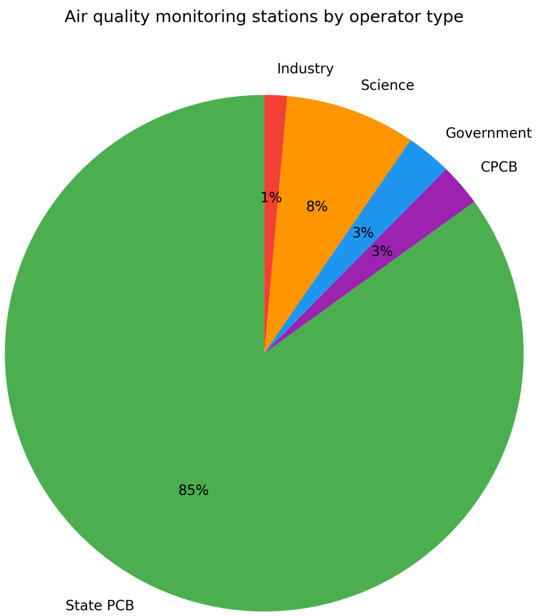


At the same time, the correlations are still far from strong. Automatic stations provide fast and frequent observations, which greatly improves situational awareness, but they cannot measure the full range of pollutants. For this reason, manual monitoring networks remain essential — especially in high-pollution regions — to capture parameters that automated systems cannot detect and to maintain a complete assessment of air quality.

Operators of India’s Continuous Air Monitoring System

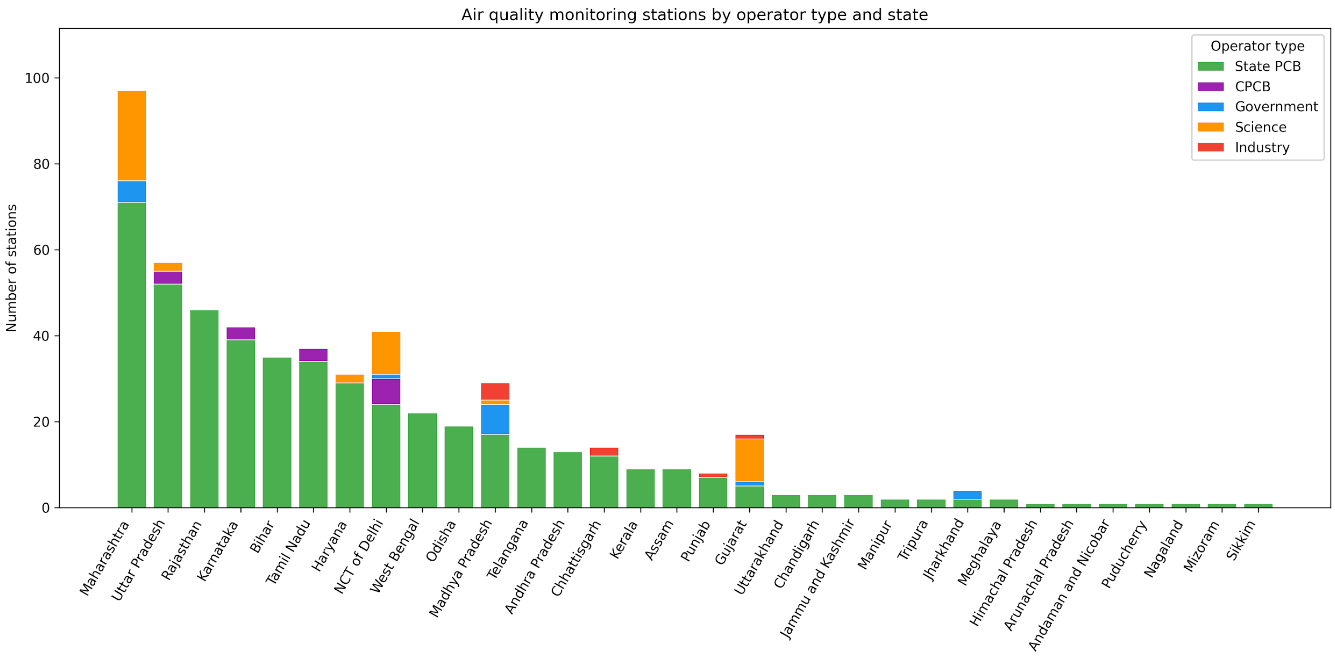
The CAAQM network is operated by 51 distinct agencies, according to the 2025 station list. The vast majority of stations are operated by State Pollution Control Boards (SPCBs), which manage 481 monitoring sites across the country. These boards represent the regional branches of India’s environmental regulatory system and are responsible for implementing national monitoring programs and operating most stations within their respective states. The central regulator, the Central Pollution Control Board (CPCB), directly operates a smaller share of the network, with 15 stations distributed across several states.





Scientific institutions constitute the second most significant group of operators, managing 46 stations in total. Indian Institute of Tropical Meteorology (IITM) also manages the SAFAR program, which runs automated air quality stations in major metropolitan areas and reports data through the same national platform.

The largest contributors to the network by station count include MPCB (Maharashtra), UPPCB (Uttar Pradesh), RSPCB (Rajasthan), KSPCB (Karnataka), TNPCB (Tamil Nadu), IITM, BSPCB (Bihar), and HSPCB (Haryana). These agencies collectively account for a major share of operational CAAQM stations.

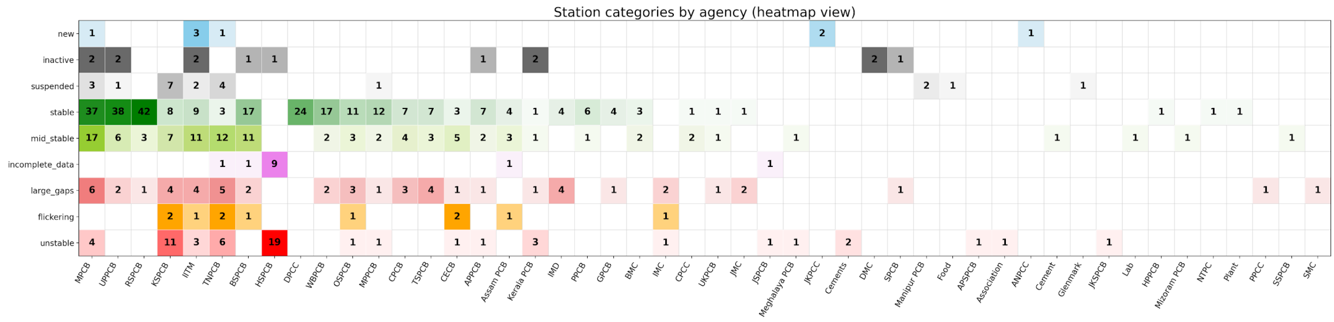


In several small states and union territories — small either in population or geographic area — only a single CAAQM station is present, and these sites are typically operated by the respective State Pollution Control Boards or Pollution Control Committees.

Government bodies outside the environmental regulatory system also participate in operating monitoring stations. Sixteen stations are run by municipal or governmental authorities, including large urban administrations such as the Brihanmumbai Municipal Corporation, the Delhi Municipal Corporation, the Indore Municipal Corporation, the Jaipur Municipal Corporation, and the Surat Municipal Corporation, as well as national ministries such as the Ministry of Housing and Urban Affairs. These stations often form part of local urban environmental monitoring initiatives.

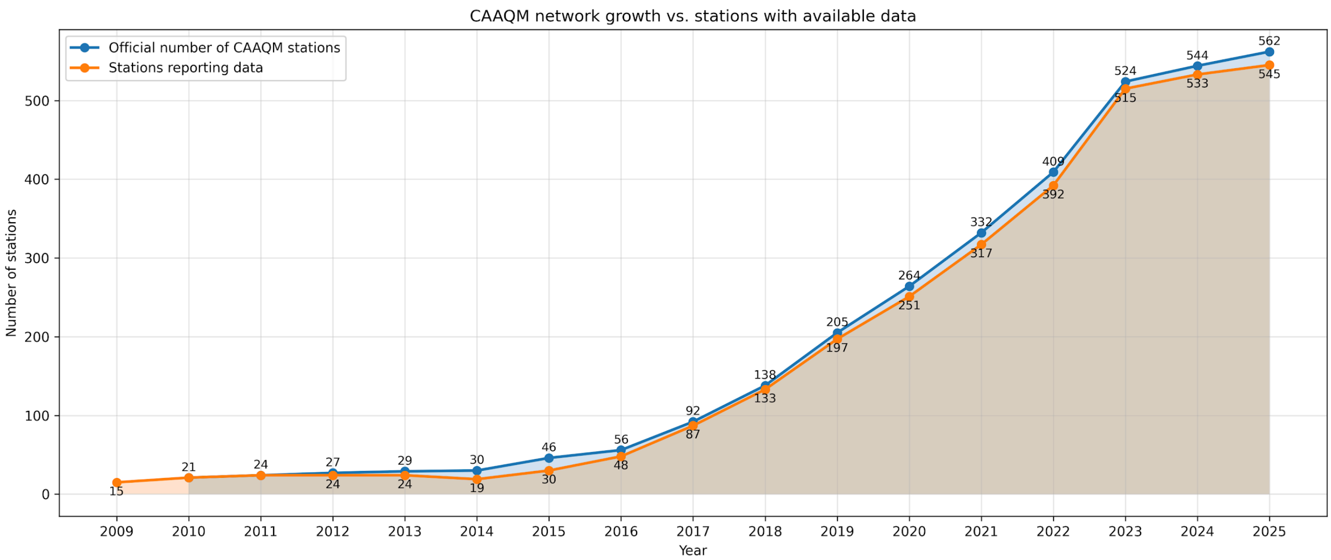
A smaller but notable share of stations is operated by industrial actors. Eight monitoring sites are associated with industrial enterprises or industrial associations. Examples include facilities linked to companies such as NTPC (National Thermal Power Corporation) and Glenmark Pharmaceuticals, as well as monitoring stations established within industrial clusters such as the GIDC Nandesari industrial estate in Gujarat. These stations typically serve environmental compliance and industrial emissions monitoring purposes.

Overall, the network combines stations operated by state regulatory bodies, central agencies, and research institutions.

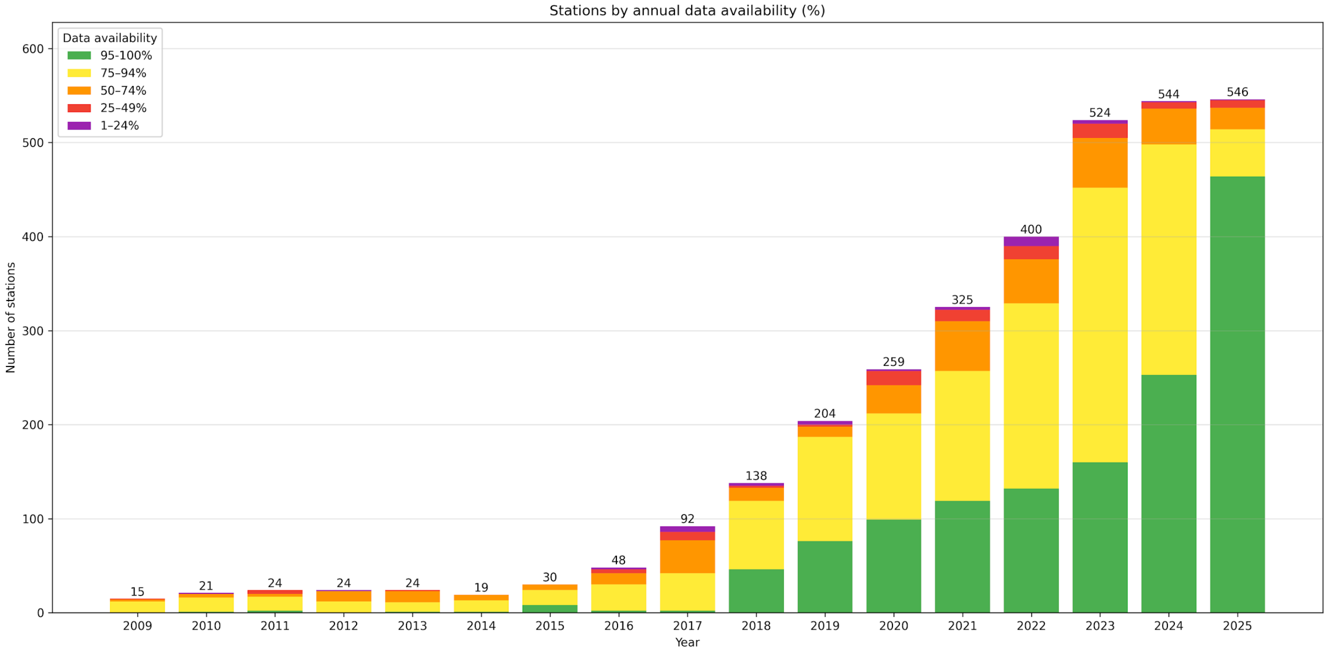


Data Availability and Continuity of Observations

India's air quality networks provide extensive public access to electronic datasets, yet the availability of real-time measurements is not uniform. As the figure shows, some stations that appear in the official lists for certain years have no publicly accessible data at all. The divergence between the "official" number of CAAQM stations and the number of stations actually reporting data indicates that commissioning, integration, and data transmission do not always occur in the same year.

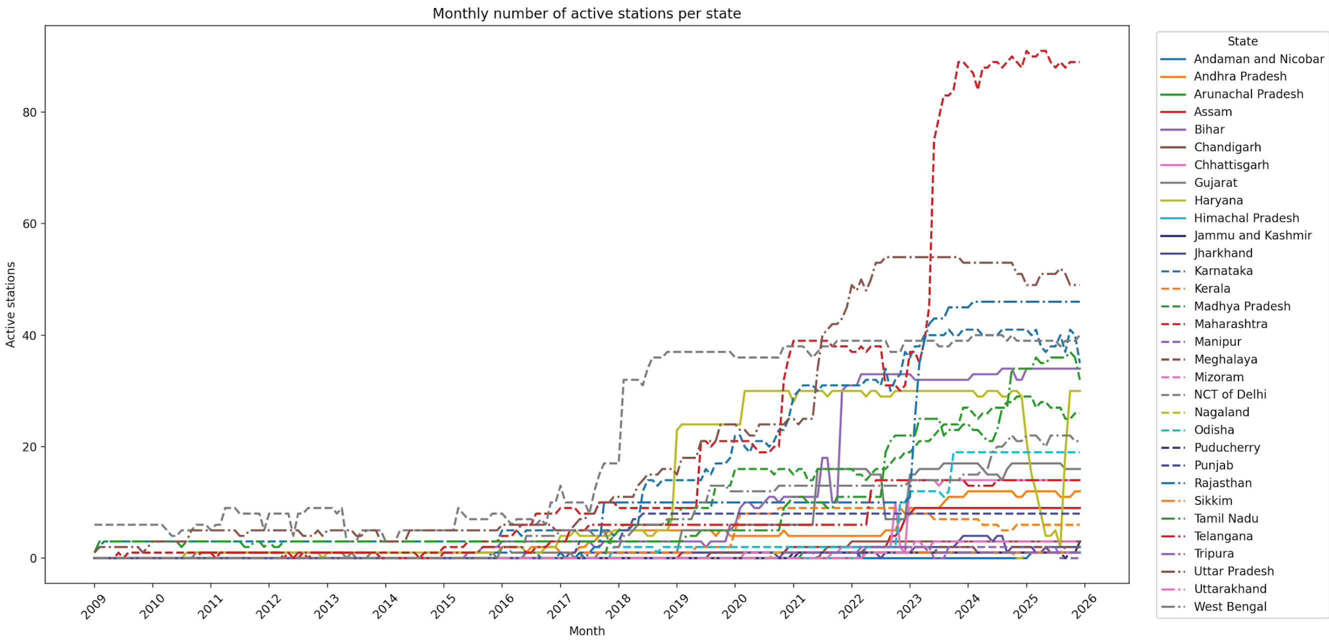


For 2025, data for most stations were available up to 10 October, reflecting the status of the central repository at the time of this study. Real-time measurements for these stations could, as a rule, also be accessed through online services for point-by-point viewing, even when their complete historical records were not yet present in the bulk archive. However, the availability of data in the repository does not necessarily imply completeness or continuity.



Stations operating for less than 1% of the year were excluded from the analysis.
Data for 2025 were evaluated for the period from 1 January to 10 October.

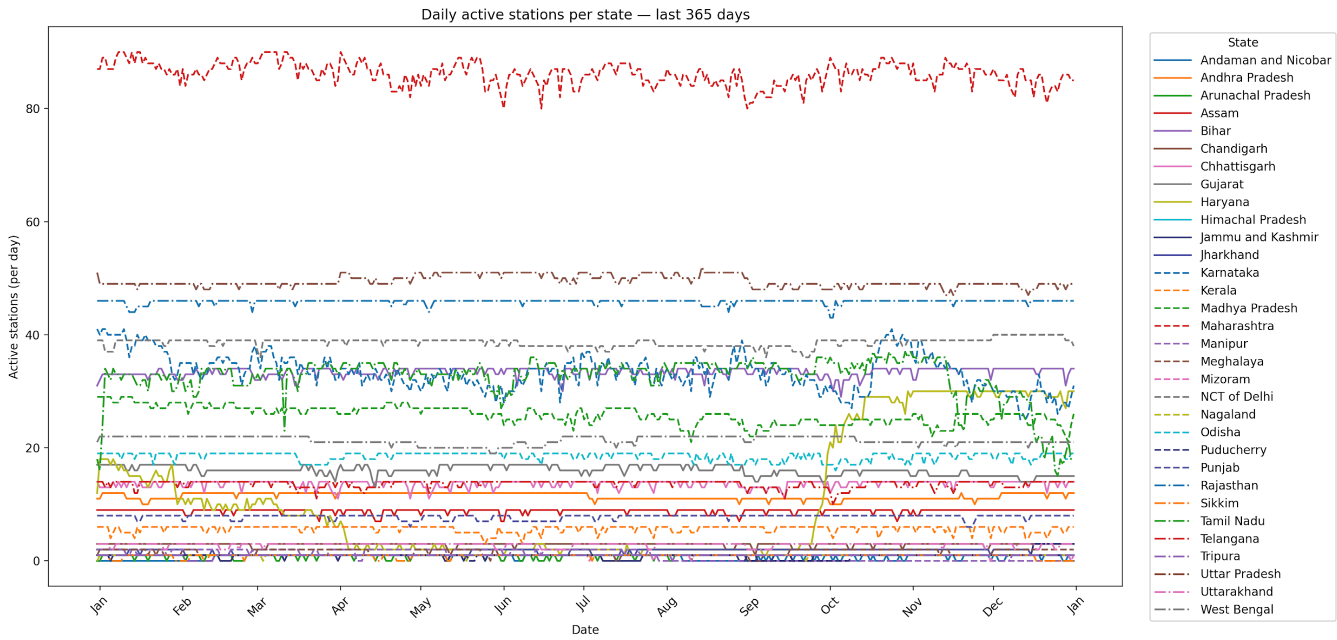
Some stations supply continuous data, while others exhibit recurring or long-lasting interruptions. Around half of the stations provide stable, high-availability data. The remaining stations experience interruptions of varying duration. For most of them, the total downtime does not exceed 25% working time of the year, although some stations report only fragmentary data.



When data availability is assessed at the state level, it becomes clear that some states maintain more stable data transmission than others. Certain anomalies are also visible — for example, periods of sustained uninterrupted reporting followed by a sudden, widespread decline. The overall expansion of the network helps smooth out such disruptions, as seen in Maharashtra, where instability at individual stations is offset by their large number.

Patterns in state-level activity during the most recent year

We now turn to the analysis of data for the most recent available year (from 10 October 2024 to 10 October 2025). This period reveals several identifiable patterns and anomalies.

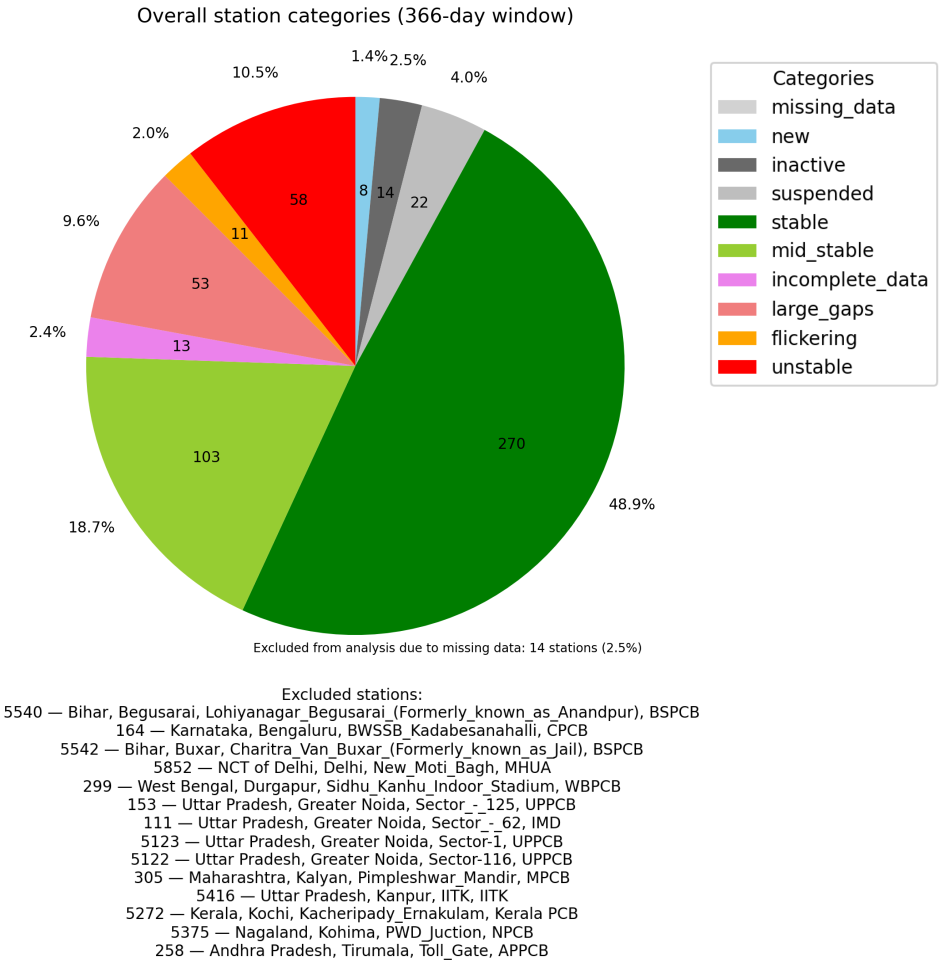


At this temporal scale, it is also evident that some states maintain relatively stable data transmission, while others show highly uneven behavior. To investigate the underlying reasons for these differences, we grouped stations into several categories based on their activity profiles.

Category	Description
New	Stations that became active for the first time within the last 365 days.
Inactive	Stations that stopped transmitting data before the beginning of the analysed period and have not been active since.
Suspended	Stations that were active during the analysed period but have been offline for more than 30 consecutive days.
Stable	Stations with near-ideal data transmission: high data volume, very few interruptions, and no prolonged outages. They provide more than 90% data completeness over the period, have only minimal downtime, and no individual interruption exceeds two days.
Mid stable	Stations that maintain generally good performance: more than 75% data completeness, no more than ten interruptions per year, and none of these interruptions lasts longer than five days.

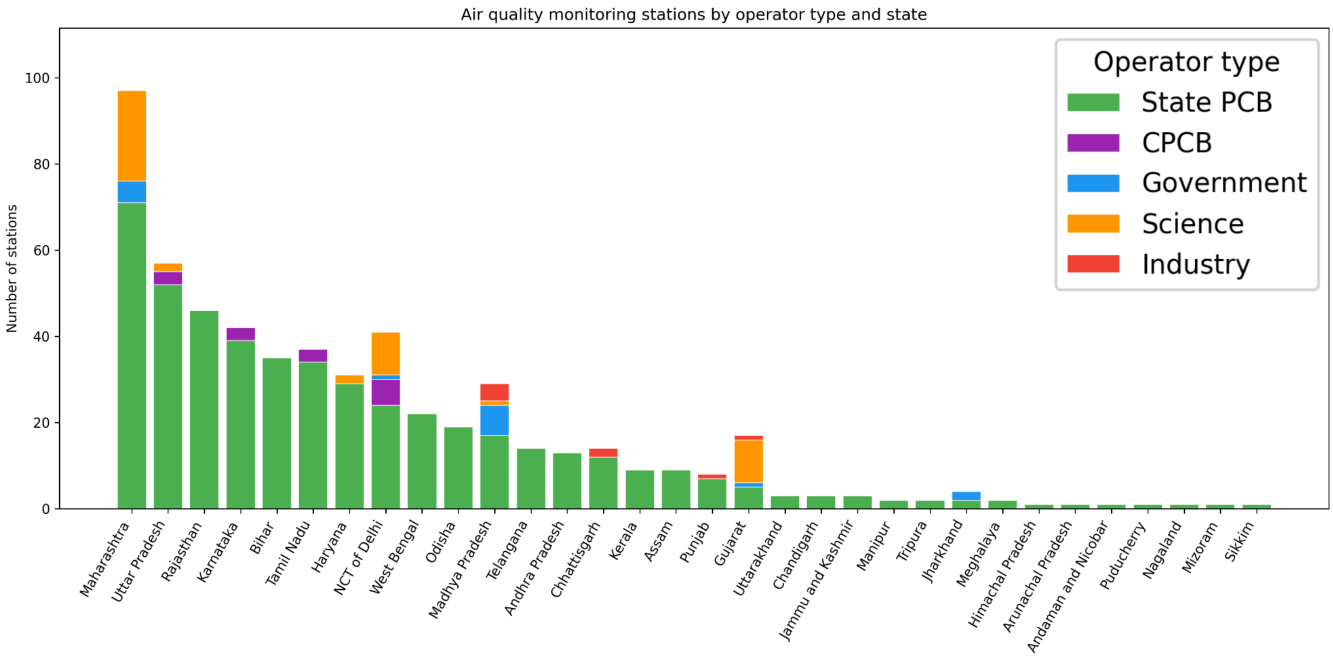
Unstable	Stations with strongly incomplete data, frequent interruptions, long outages, or a combination of several weaknesses.
Incomplete data	Stations that provide an insufficient overall volume of data. This may occur either because they transmit only a limited number of valid hours per day, or because they remain inactive for a large part of the year but operate steadily once they return online.
Large gaps	Stations that generally transmit a substantial amount of data and operate relatively steadily but experience one or more clearly pronounced long interruptions.
Flickering	Stations that provide data overall and do not have large outages, but frequently interrupt transmission — many short stops lasting up to three days.

We excluded from analysis three stations that appeared in historical lists but are no longer present in the current station inventory or whose pages have disappeared from the repository.

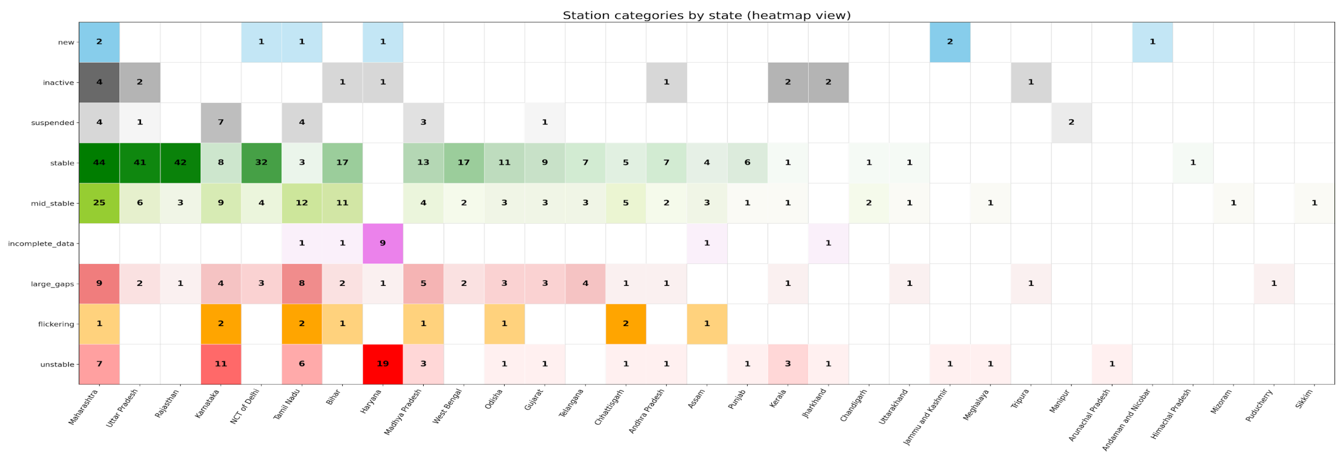


When the stations are grouped by activity categories, nearly half demonstrate stable performance over the past year, while the remainder are distributed across several types of irregular behaviour. A substantial share — around 17% — falls into the category of moderately stable stations, which generally perform well but exhibit some interruptions. A smaller portion consists of stations that are new, no longer transmitting, or have recently gone offline.

Large states with extensive monitoring networks display clear internal contrasts. Maharashtra, for example, combines the largest number of stable stations in the country with a noticeable share of stations experiencing long gaps or unstable behaviour; the size of the network helps absorb the impact of these irregularities. Uttar Pradesh also shows a mixed profile, with many stable stations but simultaneously one of the highest counts of unstable or recently extinguished stations.



In contrast, states with smaller networks tend to exhibit simpler patterns — though not necessarily better performance. Haryana, despite having a modest number of stations, includes a disproportionately high number of unstable ones. Meanwhile, compact networks such as those in Chandigarh or Puducherry consist almost entirely of stable or moderately stable stations, but the absence of redundancy makes them more vulnerable to operational disruptions.

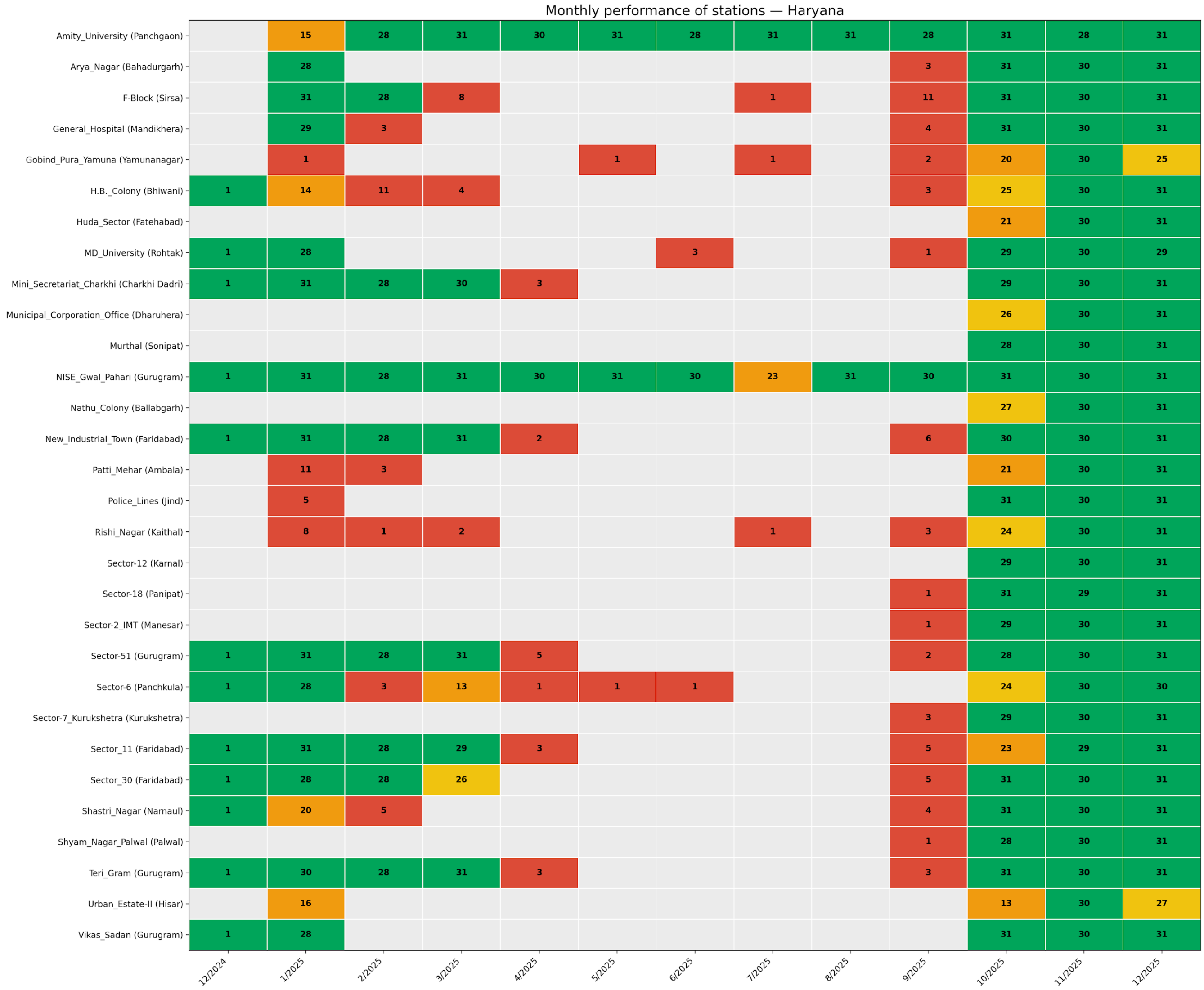


A comparison of category distributions reveals additional regional distinctions. Tamil Nadu, Gujarat, and Karnataka maintain predominantly stable networks with only a few problematic stations. Bihar and

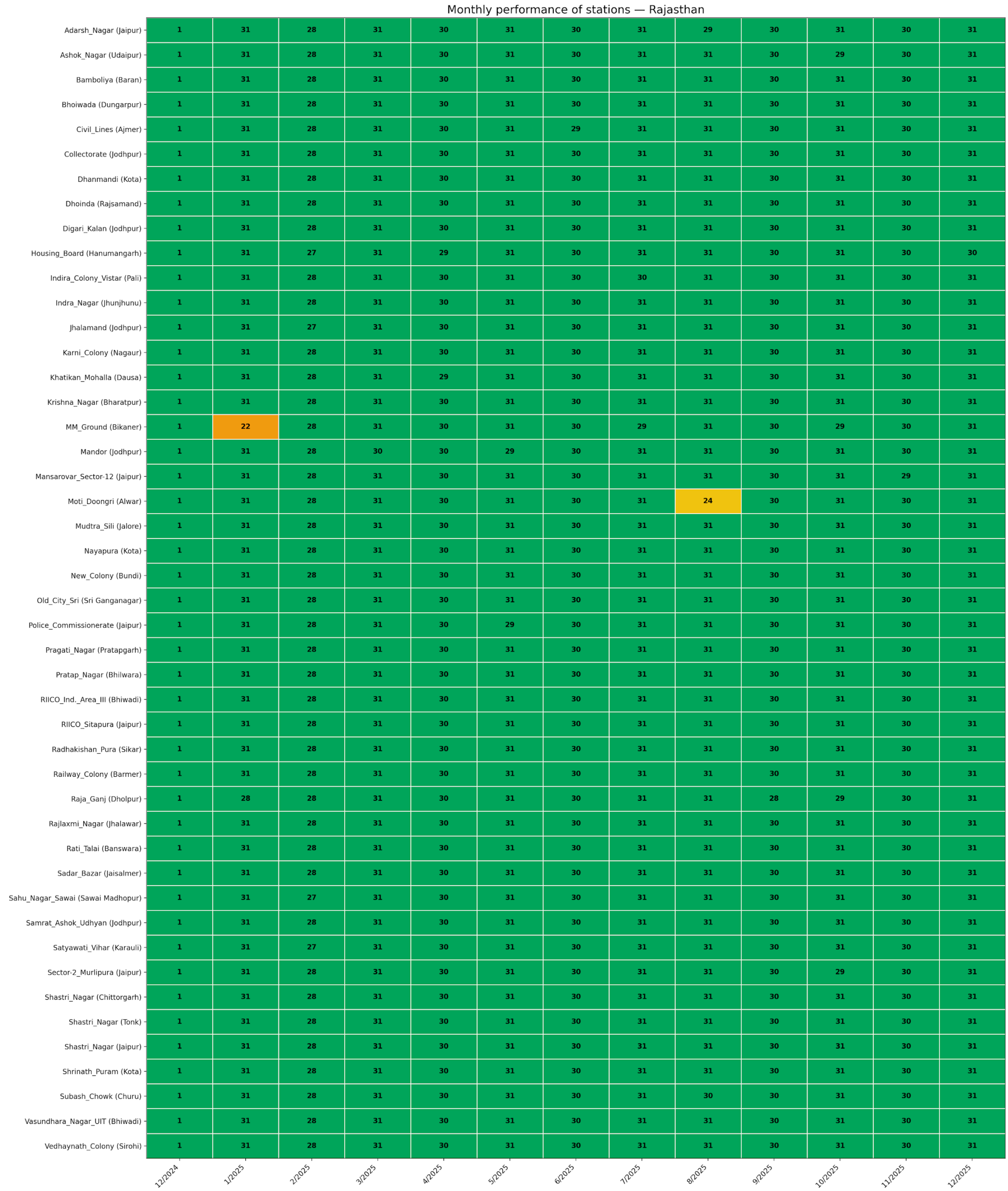
Odisha, on the other hand, show a high proportion of unstable or intermittently reporting stations, leading to uneven monitoring reliability.

To assess reliability more systematically, we compared states using the underlying metrics that define the station categories — completeness, continuity, and the length of uninterrupted gaps — which allowed us to identify the most stable and the most unstable state-level monitoring systems.

Haryana monitoring network appears as the most unstable among state level networks in the current period. Although in earlier years its network performed reliably, during the year under review almost all Haryana stations experienced extended multi-month outages, resulting in a sharp decline in overall data availability.



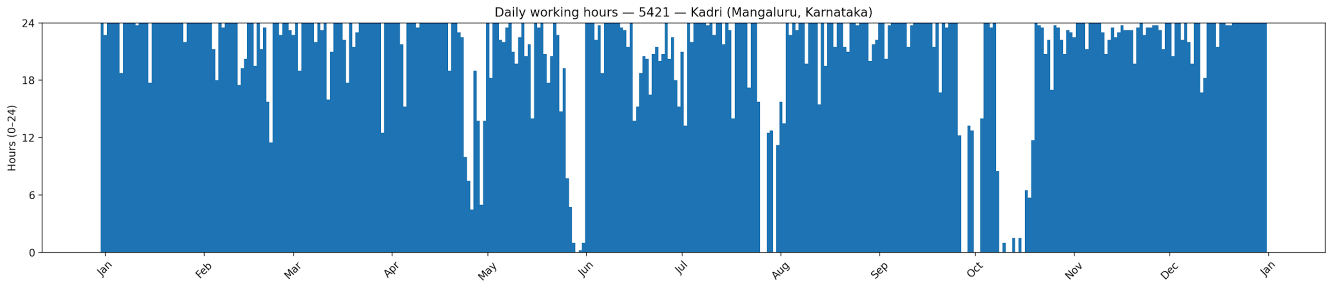
Rajasthan, in contrast, stands out as the most stable: nearly all of its stations operated continuously throughout the year, with only a few short interruptions. This pattern is consistent with previous years, as Rajasthan has maintained a high level of operational stability at least since 2021.

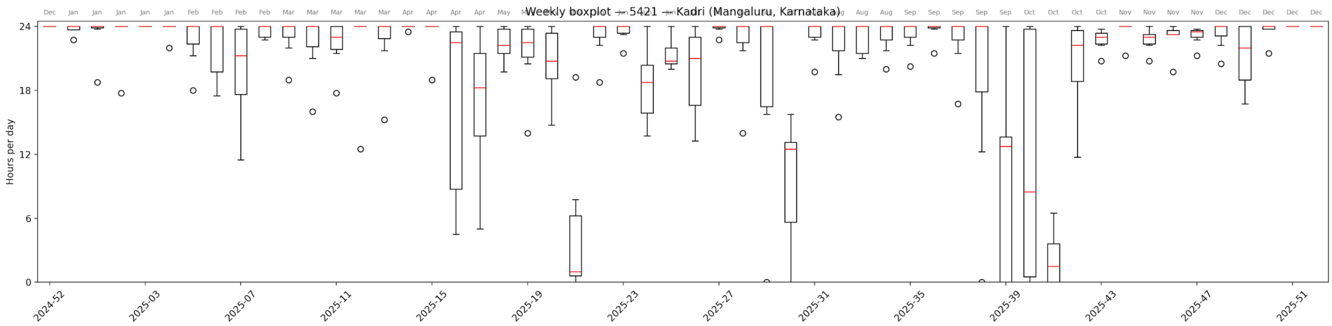


These examples illustrate that network performance varies not only in scale but also in structure.

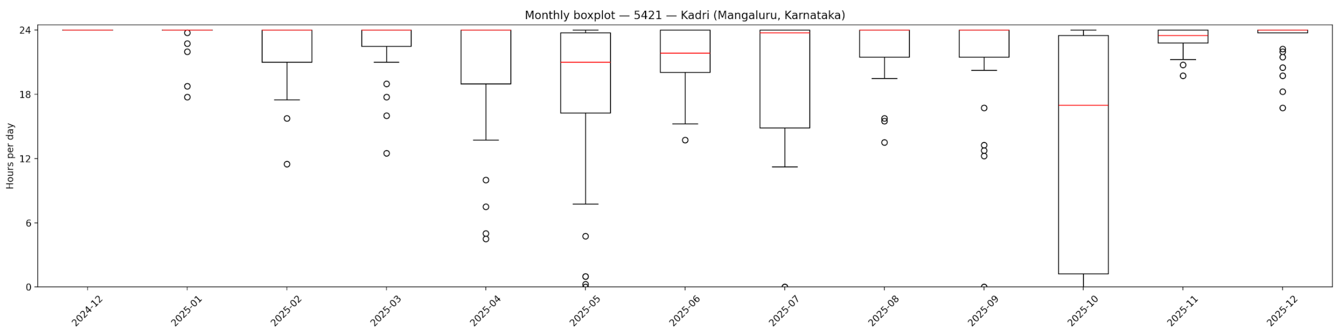
To illustrate how different patterns of data outages manifest at the station level, we selected several representative examples from the classification. These cases demonstrate the characteristic patterns associated with each category: a station with long uninterrupted gaps, a station with persistent instability and extended, a moderately stable station with recurring short disruptions, a station with regular reporting but insufficient overall data volume, and a flickering station that transmits data inconsistently with frequent short interruptions. Together, these examples provide a clearer view of the operational behaviors that underlie the broader state-level patterns described above.

Mid-stable (5421, Karnataka): the station generally reports consistently, but its monthly profiles show recurring short-duration disruptions scattered throughout the year.

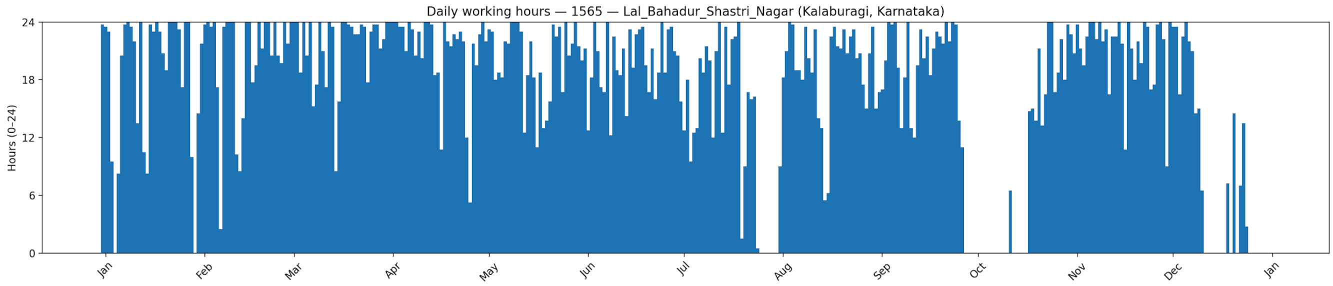


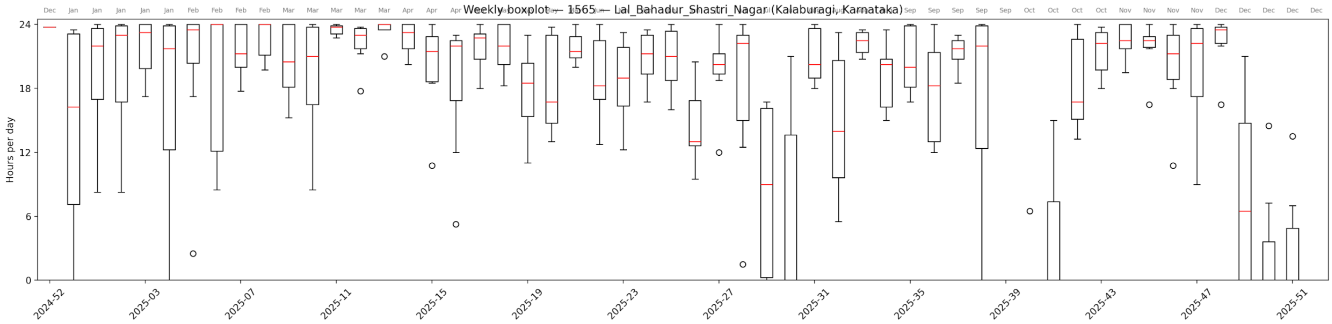


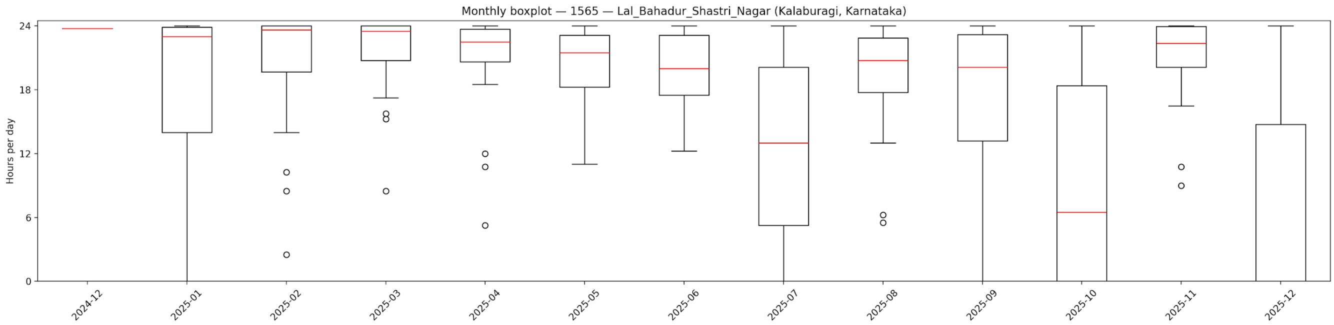
Each boxplot summarizes the distribution of the number of valid hourly measurements per day within a given time period. The central line represents the median value, while the box shows the interquartile range (the middle 50% of observations). Whiskers and points indicate the spread of the remaining values and individual outliers. The dashed red line marks the theoretical maximum of 24 hours of data per day, representing uninterrupted station operation.



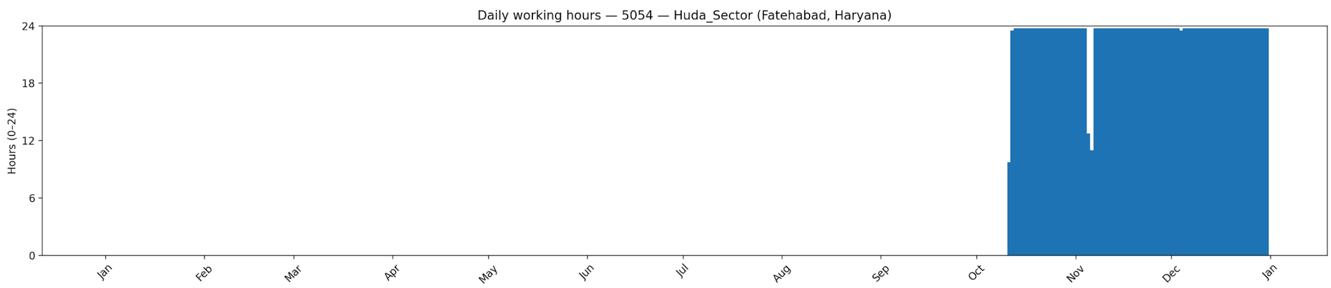
Unstable (1565, Karnataka): the station operates irregularly, daily coverage is often incomplete, and the record contains several extended gaps indicating prolonged offline periods.

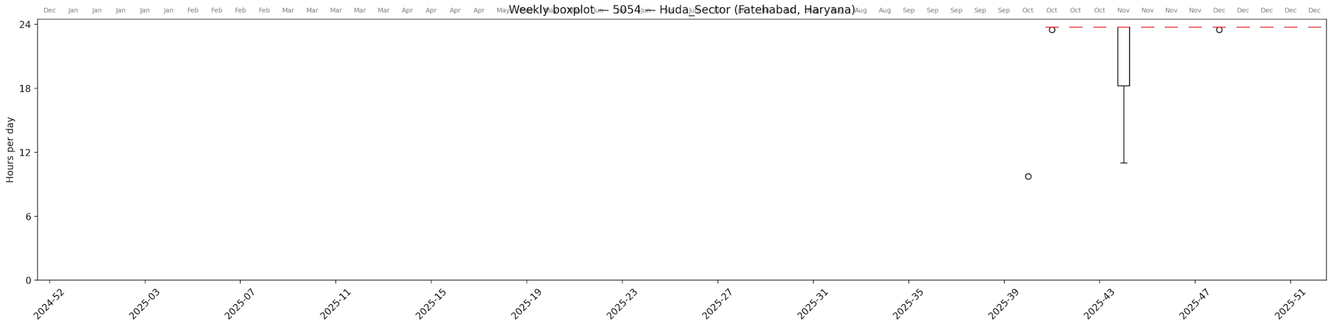


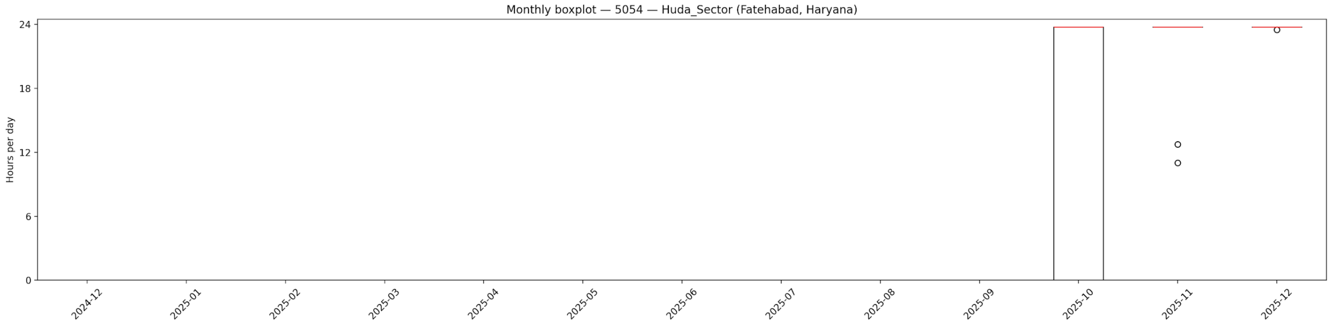




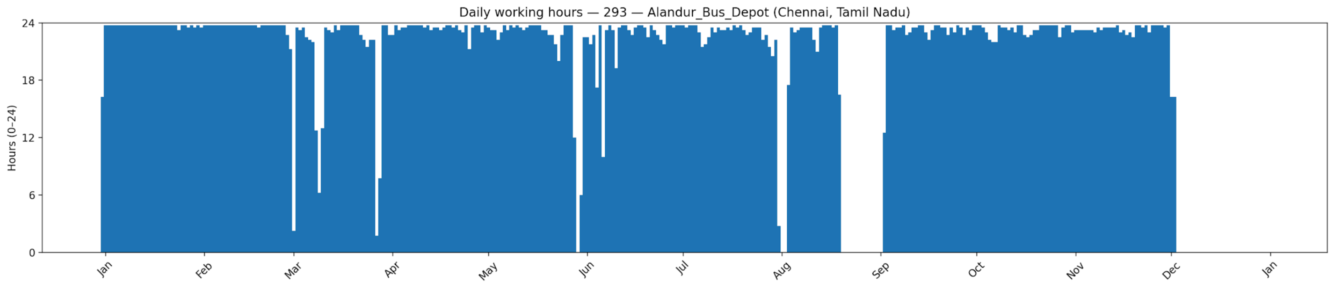
Incomplete data (5054, Haryana): this station remains inactive for most of the year and begins reporting only in Oktober, after which it operates consistently, resulting in a low total volume of data despite stable performance during the active months.

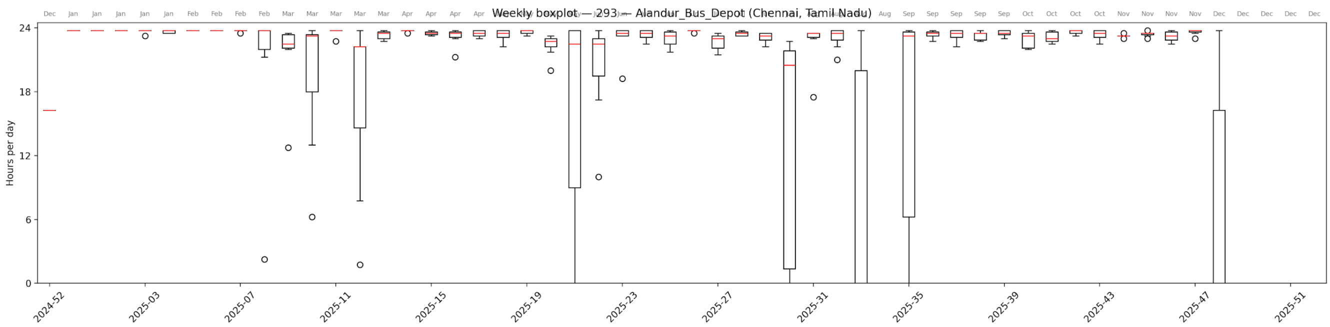


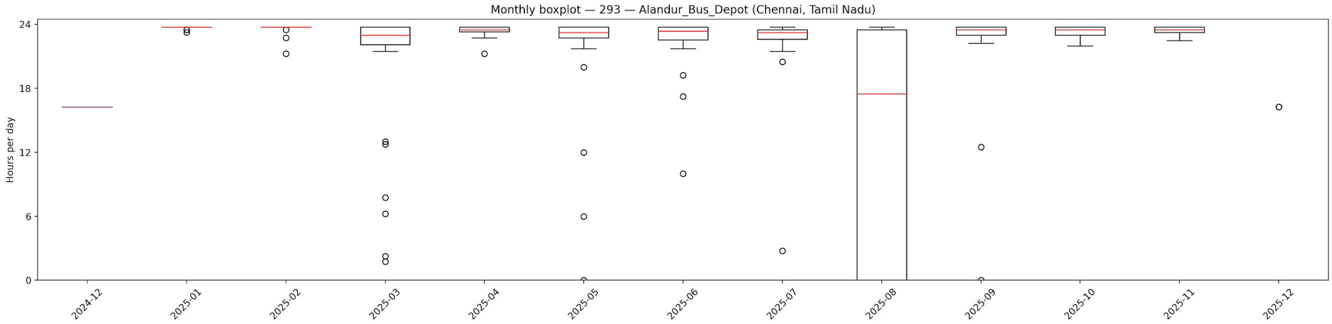




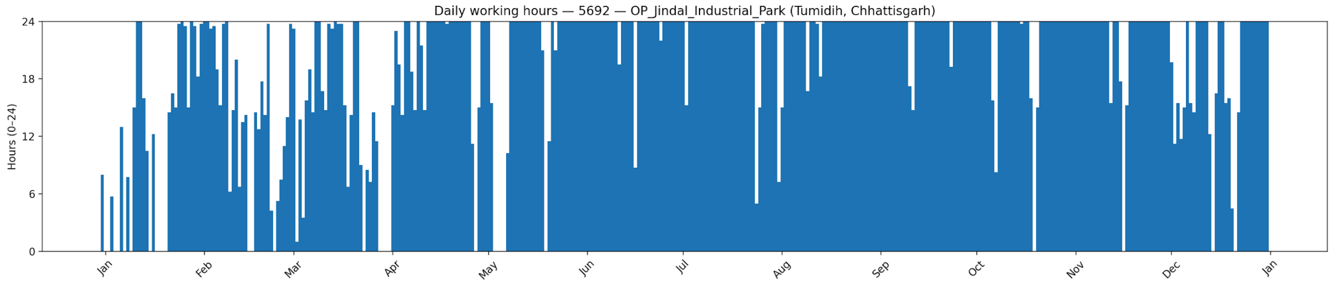
Large gaps (293, Tamil Nadu): this station operates reliably for most of the year but shows two extended outages of about three-five weeks along with several shorter gaps in transmission.

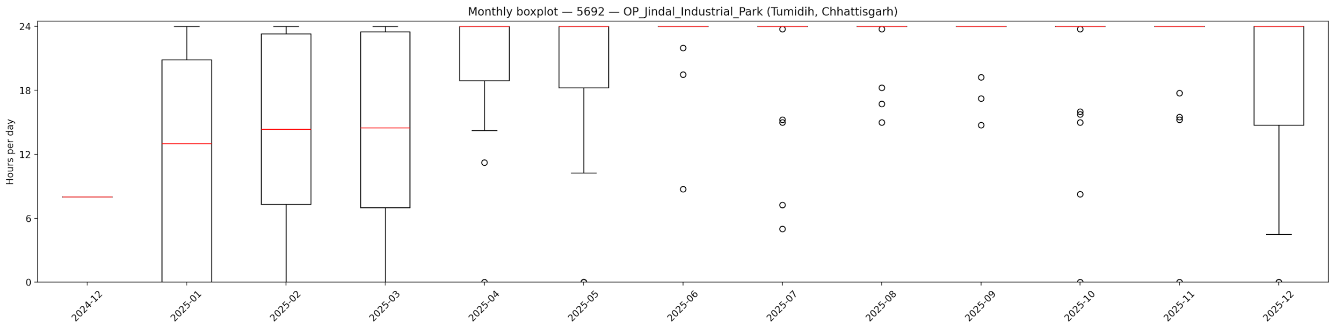


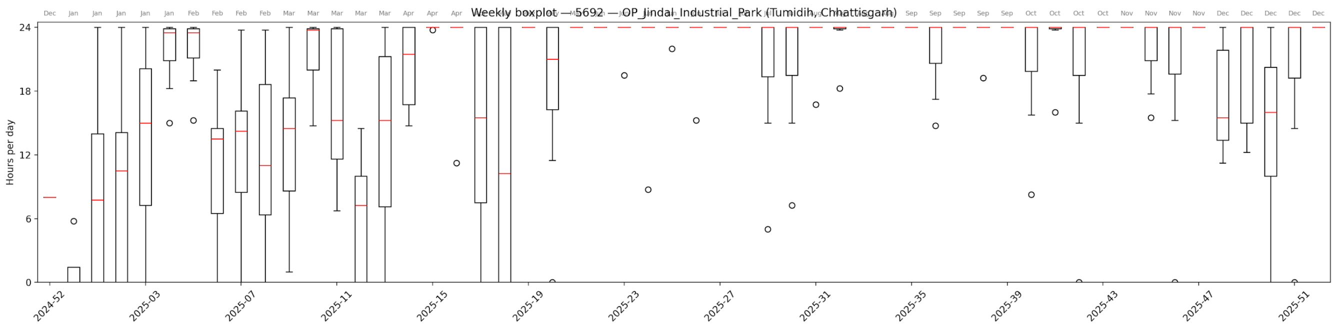




Flickering (5692, Chhattisgarh): data transmission is frequent but highly irregular, with numerous short interruptions that create a fragmented daily pattern.







Researchers did not identify any consistent patterns suggesting that stations shut down on a regular schedule—for example, for maintenance—either at the state level or within individual operating agencies. Even within the same state and under the same operator, stations may behave very differently: one may cycle on and off with many short interruptions, another may remain offline for long continuous periods, and a third may operate without a single missed day throughout the entire year.

Whether these outages are linked to weather conditions, local power failures, or network connectivity issues requires further study. Within states, neither strong positive correlations (which might indicate widespread outages caused by external factors) nor strong negative correlations (which could suggest deliberate redundancy between stations) were observed.

Seasonal fluctuations over a five-year horizon likewise reveal no clear, recurring annual pattern. However, when comparing seasons year-to-year, certain tendencies do emerge.

Opportunities for improving public air quality information systems

While the primary aim of this study was to examine the current structure and performance of India's air quality monitoring network, the analysis also points to a broader perspective on its future development. In particular, a noticeable gap remains between the rapid expansion of monitoring infrastructure and the practical usability of the resulting data for the general public. With the partial exception of regions covered by the SAFAR network, India still lacks sufficiently user-friendly tools that would allow individuals to track air quality and take timely measures to protect their health when conditions deteriorate.

A modern approach to air quality communication increasingly relies on the hyperlocalisation of data sources: residents and visitors do not typically require aggregated information for entire states or for the country as a whole, but need clear, location-specific insights into air quality in the exact area where they live, work, or plan to travel. Such hyperlocal information enables informed decisions, including the use of indoor air purification, adjustments to outdoor activities, the application of personal protective measures, or the selection of accommodation where air quality considerations are explicitly addressed.

Existing monitoring networks could therefore be complemented by easily accessible widgets integrated into widely used news platforms, meteorological websites, and mobile applications, providing locally tailored information and health-oriented recommendations. As these communication tools evolve, the challenge extends beyond the assessment of current air quality conditions toward the development of reliable short-term forecasting, which is essential for proactive public health protection and effective risk management.

Final Conclusions

India has made substantial progress in expanding its air quality monitoring capacity, developing one of the largest and most publicly accessible monitoring networks in the Global South. Both the manual NAMP network and the automatic CAAQM system experienced rapid growth in recent years, and this expansion is especially visible in major metropolitan regions and in cities that serve as national hubs of industry, services, and high-technology development. In these areas, the density of stations and the availability of real-time data have increased markedly, enabling broader public access and more reliable environmental information.

According to the latest data, the states of Maharashtra, Uttar Pradesh, and West Bengal host the most extensive air quality monitoring networks in the country, each operating more than 100 active stations across all monitoring programmes.

However, the geographical distribution of monitoring infrastructure remains uneven. Several states and union territories — such as Ladakh, Lakshadweep, Goa, and Dadra and Nagar Haveli and Daman and Diu — still lack continuous monitoring, relying solely on manual stations whose results are not available to the public in real time. Many medium-sized cities and numerous districts operate only one or two stations, and a significant share of the population continues to live outside the reach of continuous air quality measurement.

A closer comparison between the monitoring capacity observed in this study and India's own siting guidelines reveals a more nuanced picture. The population-based norms outlined in CPCB's Guidelines for Ambient Air Quality Monitoring (2003) are largely met in major cities: most large non-attainment and metropolitan areas operate the minimum required number of manual NAMP stations, and typically include at least one CAAQM site. By the standards of India's internal regulatory framework, coverage in the largest cities is therefore close to adequate.

Yet when monitoring density is examined across the wider system of urban settlements, the situation looks less balanced. Many cities with populations between 300,000 and one million — precisely the range undergoing the fastest demographic and industrial growth — have only one or no automatic stations. In some cases, their monitoring relies entirely on manual observations. While this technically satisfies Indian norms, which do not mandate a specific ratio of automatic stations, it falls short of contemporary expectations for real-time environmental data availability. At the district level, gaps are even more pronounced: around 40% of districts lack any government-operated monitoring site.

When benchmarked against international practice, the deficit becomes more evident. In many countries with mature air quality systems, urban areas typically maintain one automatic station per 100,000–300,000 inhabitants. In India, most cities above 300,000 residents have fewer than one automatic station per 100,000 residents, and only the largest megacities — Delhi, Mumbai, Ahmedabad — approach densities comparable to international norms. Closing this gap would require the establishment of additional CAAQM sites, particularly in medium-sized cities, peripheral districts of highly polluted states, and currently unmonitored union territories.

Operational reliability is the second major challenge identified by this study. Although roughly half of CAAQM stations provide regular data and a substantial share show consistent performance, a significant minority continue to experience long outages, frequent short interruptions, or incomplete data transmission. Progress is evident—data availability improves year by year—but the inconsistency of station performance remains an important constraint on the overall effectiveness of the monitoring system and requires further investigation. Understanding the drivers behind outages—whether linked to power supply, network connectivity, equipment performance, or administrative factors—will be crucial for ensuring that the existing infrastructure delivers the level of service required for public health protection and environmental governance.

Taken together, the findings point to a dual reality. India has achieved remarkable growth in its monitoring networks, making real-time air quality data accessible to millions of urban residents and expanding its capacity far beyond what existed a decade ago. Yet significant gaps remain: continuous monitoring is still unavailable across several regions, medium-sized cities are under-instrumented relative to their population and pollution burden, and many automatic stations do not yet provide the stable, uninterrupted datasets that policy-makers, researchers, and the public increasingly depend on. Addressing these gaps will be essential if India is to align not only with its own population-based norms but also with international expectations of comprehensive, reliable, and timely air quality information.

Acknowledgments

We extend our sincere appreciation to the **Central Pollution Control Board (CPCB)** for providing open access to national air quality datasets, including the CAAQM real-time platform and official inventories of monitoring stations. These publicly available resources form the backbone of this research and enable nationwide assessments of monitoring coverage across India's states, districts, and cities.

We gratefully acknowledge the **National Ambient Air Monitoring Programme (NAMP)** and the institutions responsible for maintaining manual monitoring sites throughout the country. Their long-standing data collection efforts provide an essential foundation for understanding air quality conditions beyond the automatic station network.

We thank the **Indian Institute of Tropical Meteorology (IITM)** for maintaining the SAFAR monitoring system, whose publicly available station metadata and geospatial information were used to complement national network inventories.

We also recognize the contributions of global scientific institutions whose openly accessible datasets made this research possible. In particular, we acknowledge the **Atmospheric Composition Analysis Group** (Washington University in St. Louis) for their high-resolution global $PM_{2.5}$ product, the **Joint Research Centre (JRC)** of the European Commission for the GHSL population grids, the **United Nations Department of Economic and Social Affairs (UN DESA)** for the World Urbanization Prospects dataset, and the **Development Data Lab** for the SHRUG geospatial and demographic platform.

We extend our gratitude to the many researchers, engineers, and analysts whose earlier work on air quality monitoring, sensor technologies, and health impacts provided essential scientific context for this study. Their contributions have greatly enriched the analytical framework and interpretation of results.

Finally, we acknowledge all individuals and organizations committed to advancing transparency, accessibility, and scientific rigor in environmental data. Their sustained efforts not only make studies of this scale possible, but also strengthen public understanding of air quality challenges across India.

Sources and references

[1] Central Pollution Control Board (CPCB). ***Official Website***. Accessed 2025. https://cpcb.nic.in

[2] Indian Institute of Tropical Meteorology (IITM). ***SAFAR Monitoring System — Station Details***. Accessed 2025. https://safar.tropmet.res.in/

[3] Barwick, Panle Jia; Li, Shanjun; Lin Liguo; Zou, Eric; ***From Fog to Smog: the Value of Pollution Information***, NBER Working Paper No. 26541, Revision 1, 2023, http://www.nber.org/papers/w26541

[4] ***WHO global air quality guidelines***, WHO 2021, https://www.who.int/publications/i/item/9789240034228

[5] ***Personal interventions and risk communication on Air Pollution***, WHO Meeting Report, WHO 2020 https://www.who.int/publications/i/item/9789240000278

[6] Prana Air. ***Press-release: Prana Air Aids Tata Steel in Hyperlocal Air Quality Monitoring***, 2023. https://www.pranaair.com/blog/case-study-prana-air-aids-tata-steel-in-hyperlocal-air-quality-monitoring/

[7] Central Pollution Control Board (CPCB). ***Air Quality Data Portal (Real-Time System)***. Accessed 2025. https://airquality.cpcb.gov.in

[8] Atmospheric Composition Analysis Group. ***Global Surface PM2.5 Dataset*. ** Washington University in St. Louis. Accessed 2025. https://sites.wustl.edu/

[9] Joint Research Centre (JRC), European Commission. ***Global Human Settlement Layer (GHSL) — Population Grid*.** Accessed 2025. https://human-settlement.emergency.copernicus.eu/

[10] United Nations, Department of Economic and Social Affairs (UN DESA). ***World Urbanization Prospects — Urban Agglomerations Database.*** Accessed 2025. https://population.un.org/

[11] Development Data Lab. *SHRUG* — ***Socioeconomic High-Resolution Rural–Urban Geographic Platform,*** Version 2.1. Accessed 2025. https://devdatalab.org/shrug

[12] ***Methods for Measurement of Air Pollution***, Part 14, Guidelines for Planning the Sampling of Atmosphere [CHD 32: Environmental Protection and Waste Management], IS 5182-14 (2000), Bureau of Indian Standards, 2000.

[13] The Economic Times. *Over 54 lakh tourists visit Goa from Jan to June 2025*. https://m.economictimes.com/industry/services/travel/over-54-lakh-tourists-visit-goa-from-jan-to-june-2025/articleshow/122811607.cms